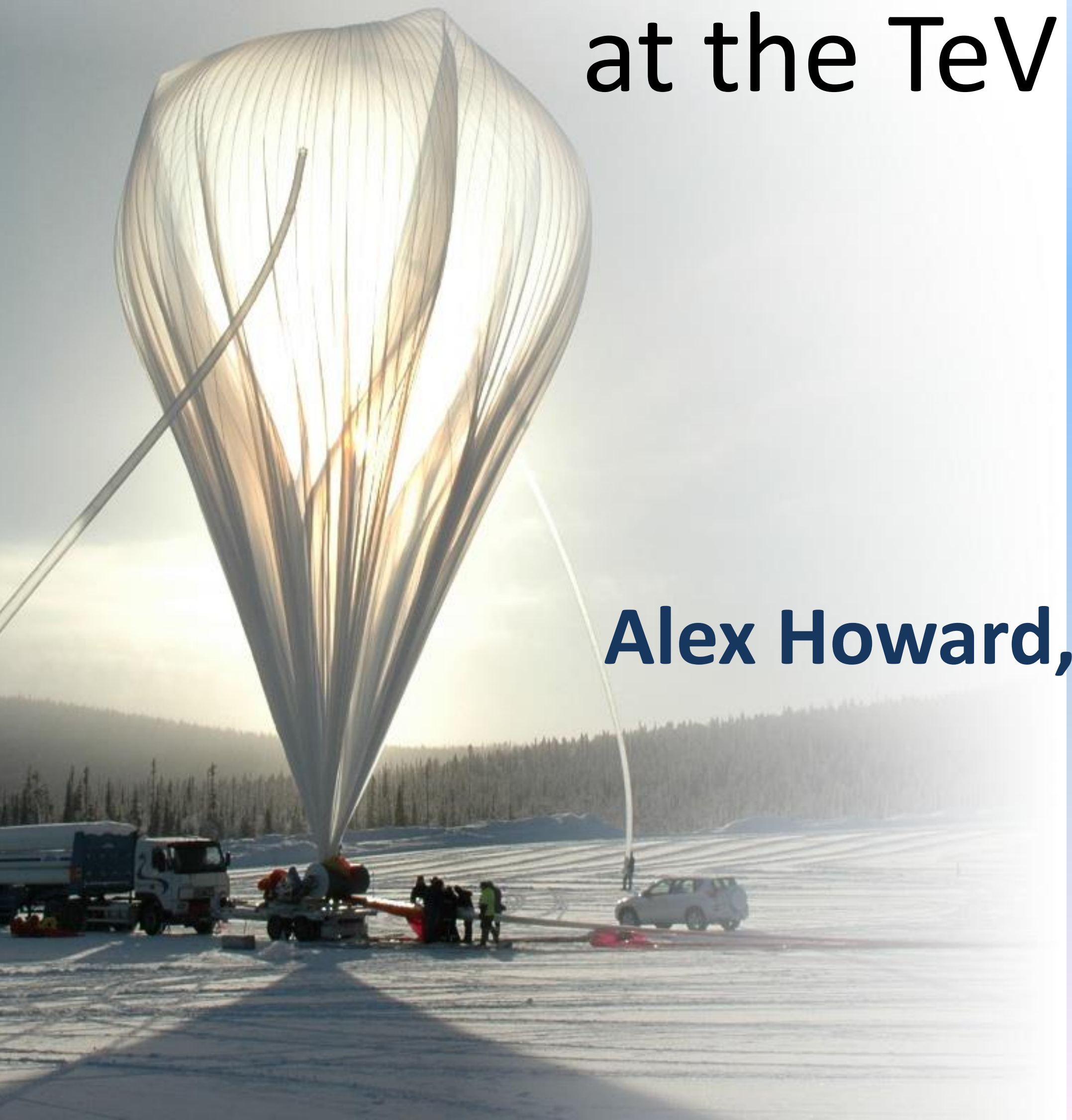
A Balloon Borne Spectrometer for Measuring Positron/Electron Spectra at the TeV Scale



Alex Howard, ETH Zurich

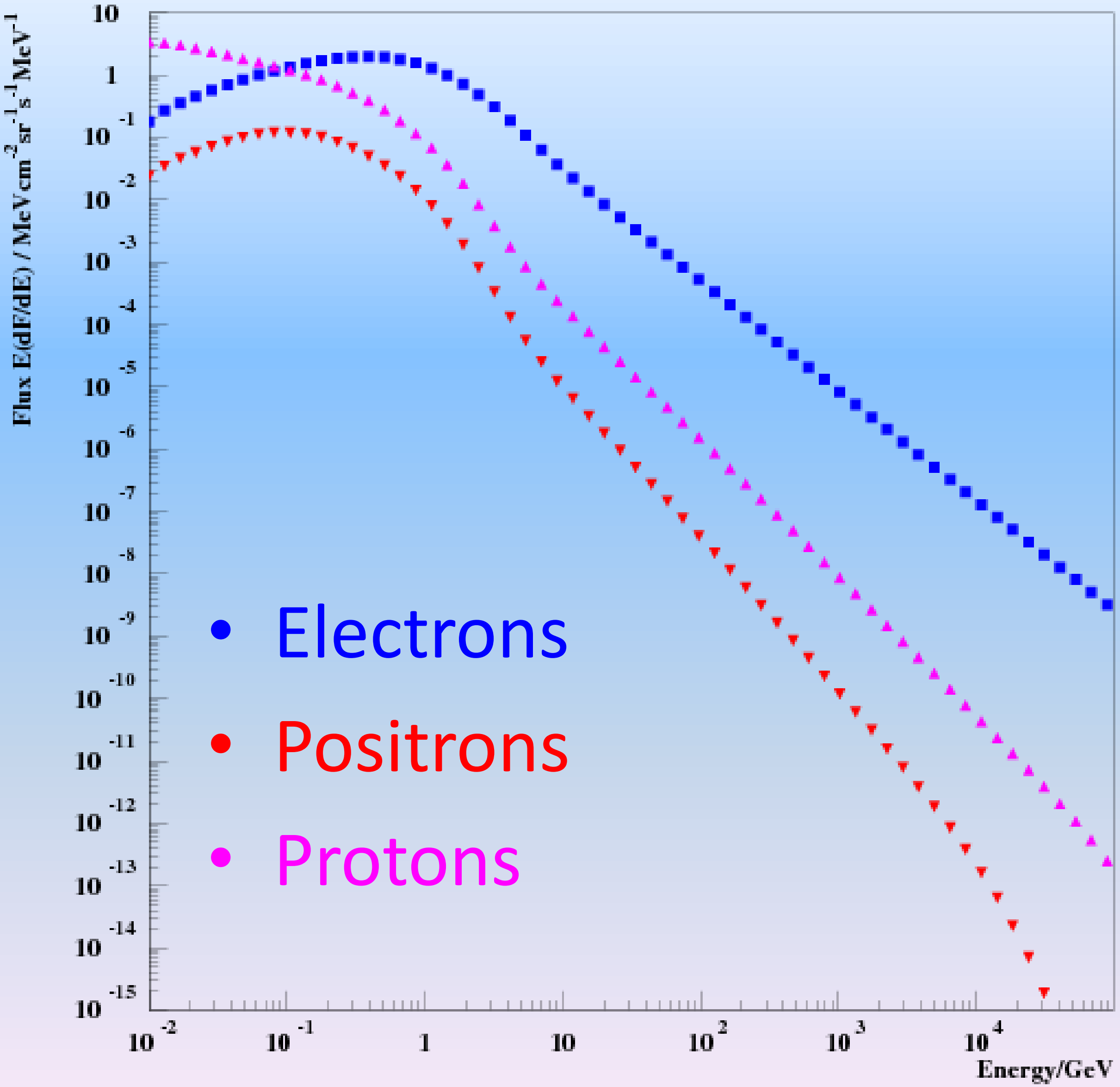
Overview

1. Why measure positrons up to 1 TeV?
2. Positron-Electron Balloon Spectrometers
3. Design concepts
4. Prototype work – Tracker/PERDAIX
5. Novel SiPM read-out
6. ECAL design and testbeam
7. Projected performance
8. Summary and Conclusions

Our Understanding (GALPROP)

- GALPROP is a numerical code for calculating the propagation of relativistic charged particles and the diffuse emissions produced during their propagation. The GALPROP code incorporates as much realistic astrophysical input as possible together with latest theoretical developments.
- http://galprop.stanford.edu/

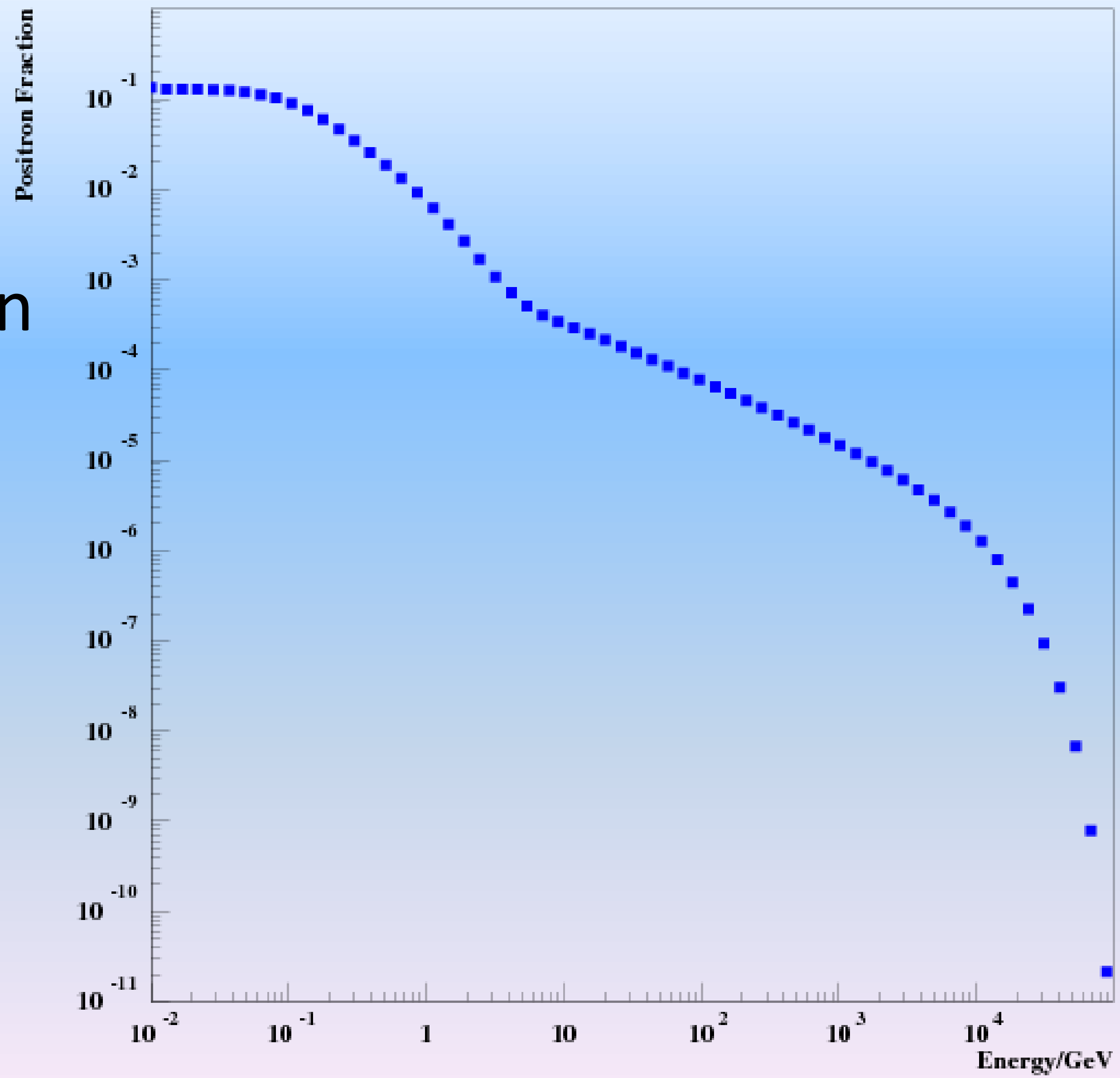
GALPROP: Cosmic Ray Fluxes

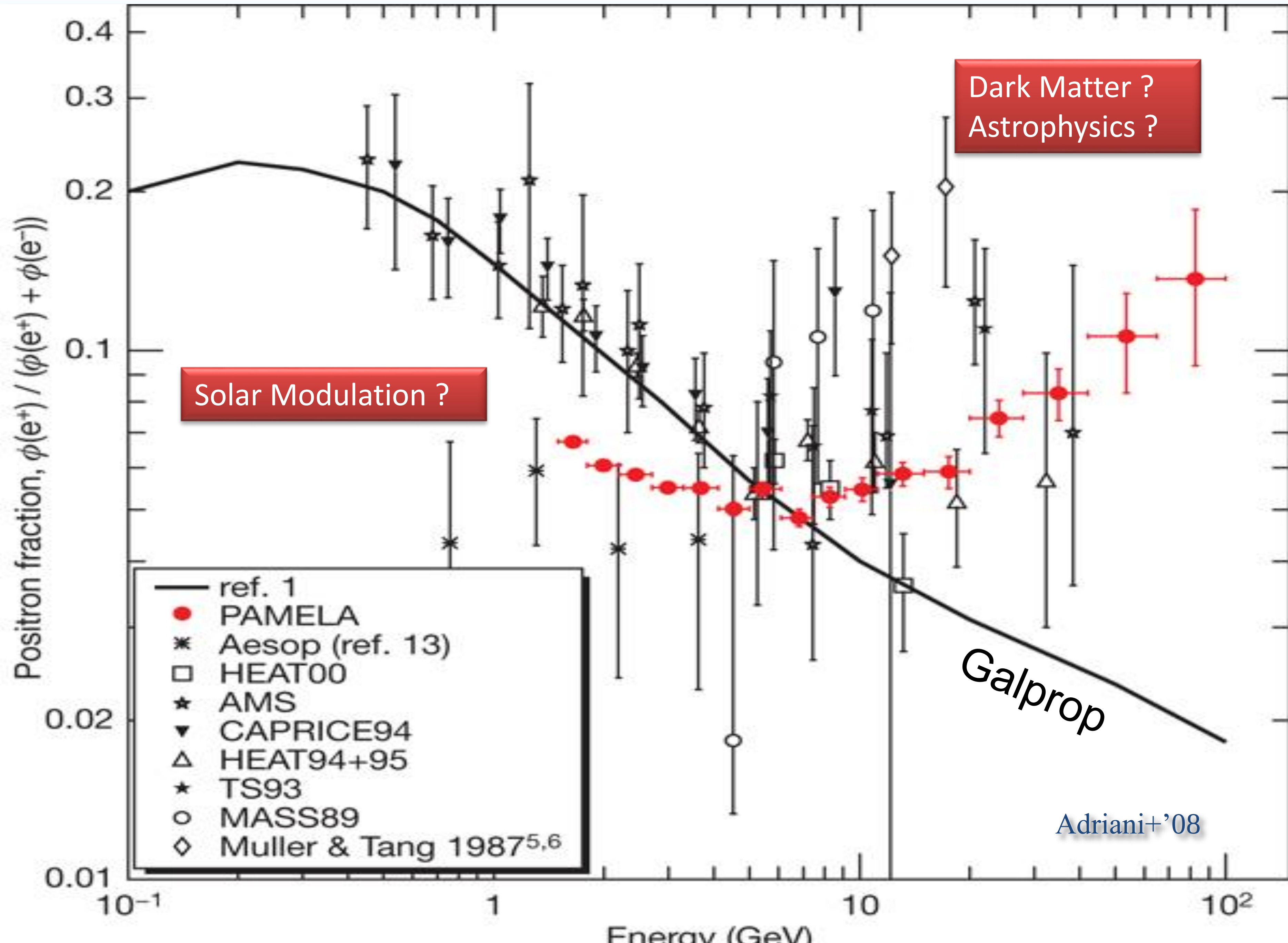


Spectra drop steeply with increasing energy

Positron Fraction

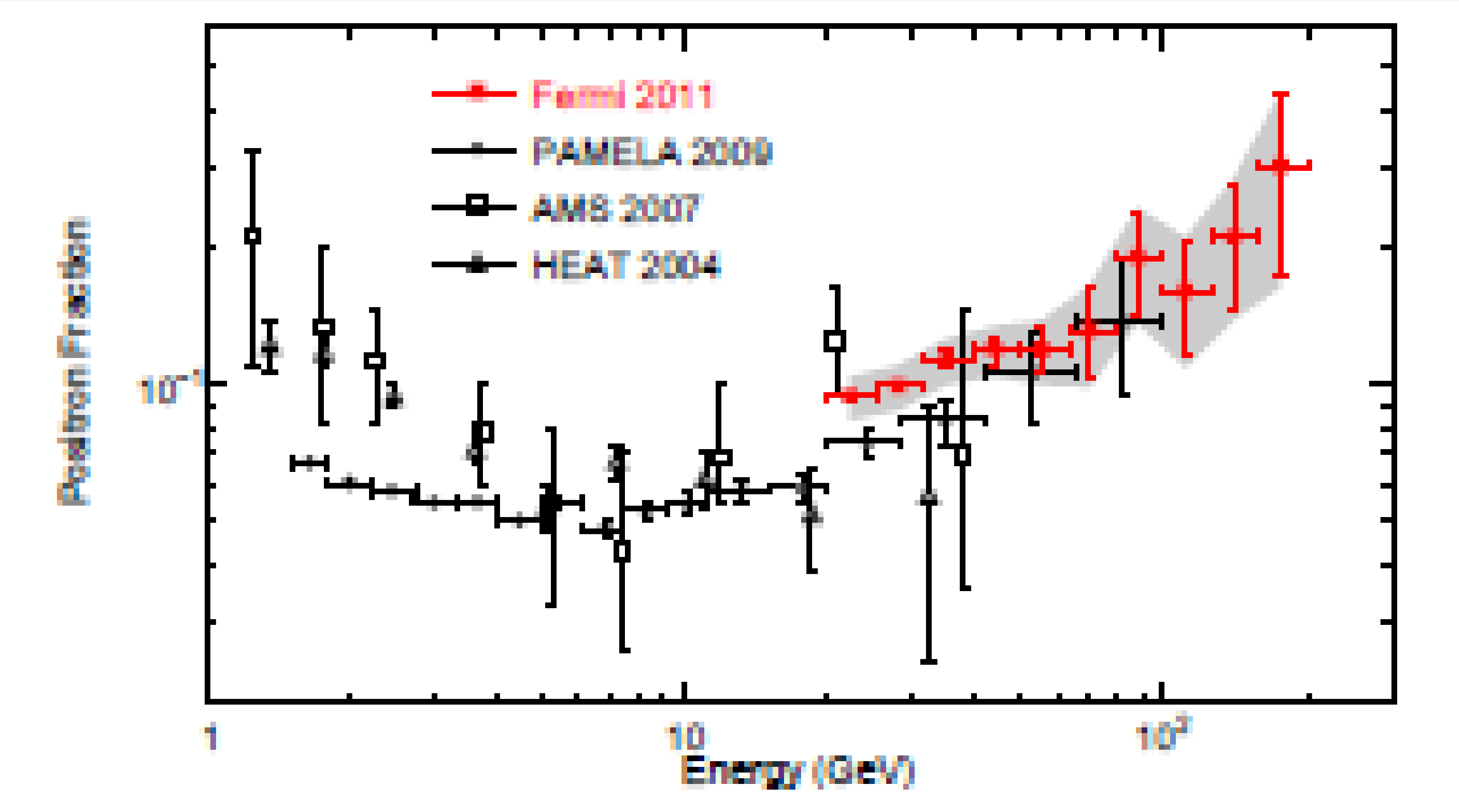
- Positron fraction decreases even more rapidly



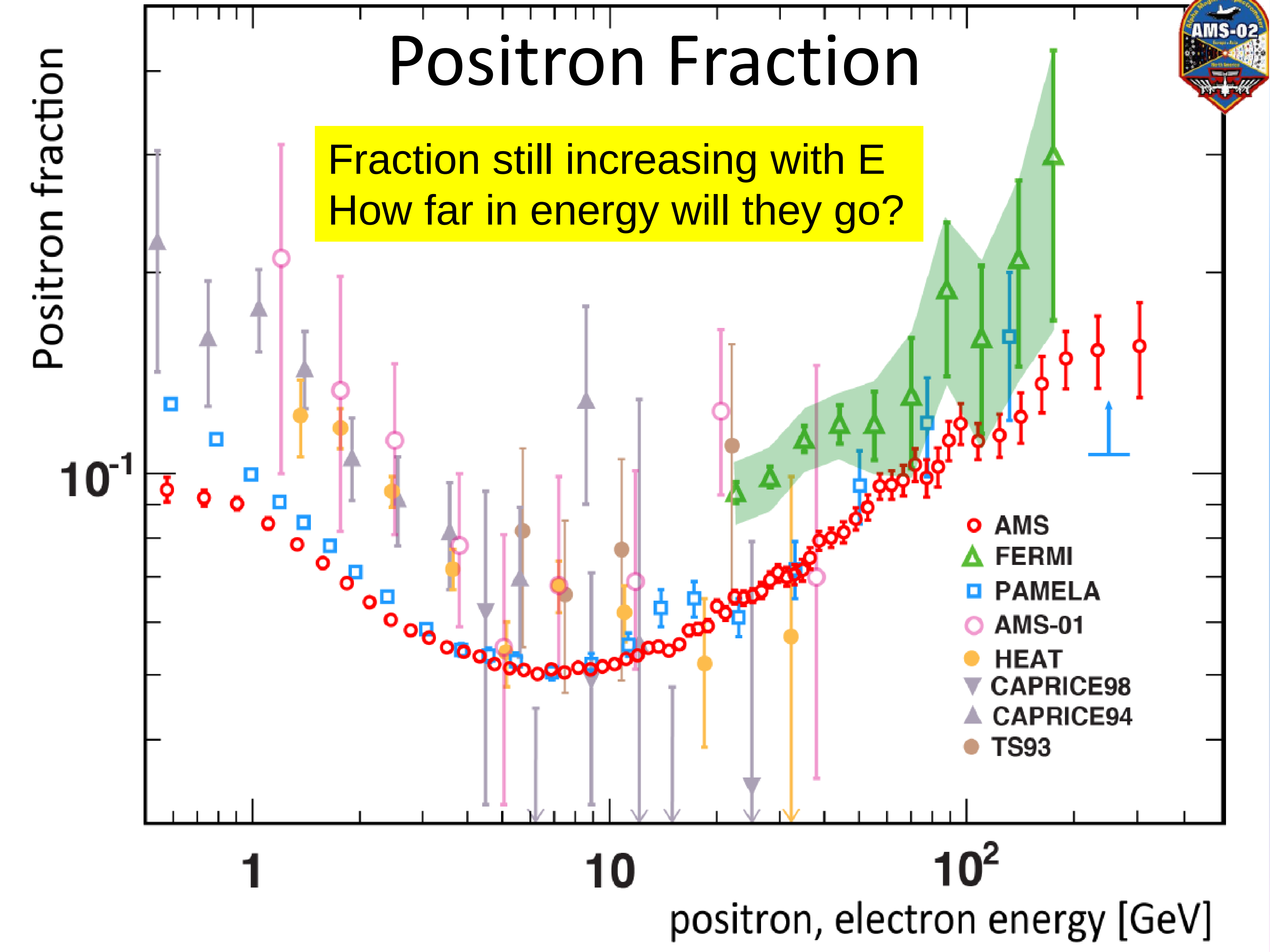


Dark Matter ?
Astrophysics ?
Solar Modulation ?
Galprop
Adriani+'08
Positron fraction, φ(e⁺) / (φ(e⁺) + φ(e⁻))
Energy (GeV)
0.4
0.3
0.2
0.1
0.02
0.01
10⁻¹
1
10
10²
ref. 1
PAMELA
Aesop (ref. 13)
HEAT00
AMS
CAPRICE94
HEAT94+95
TS93
MASS89
Muller & Tang 1987⁵˒⁶

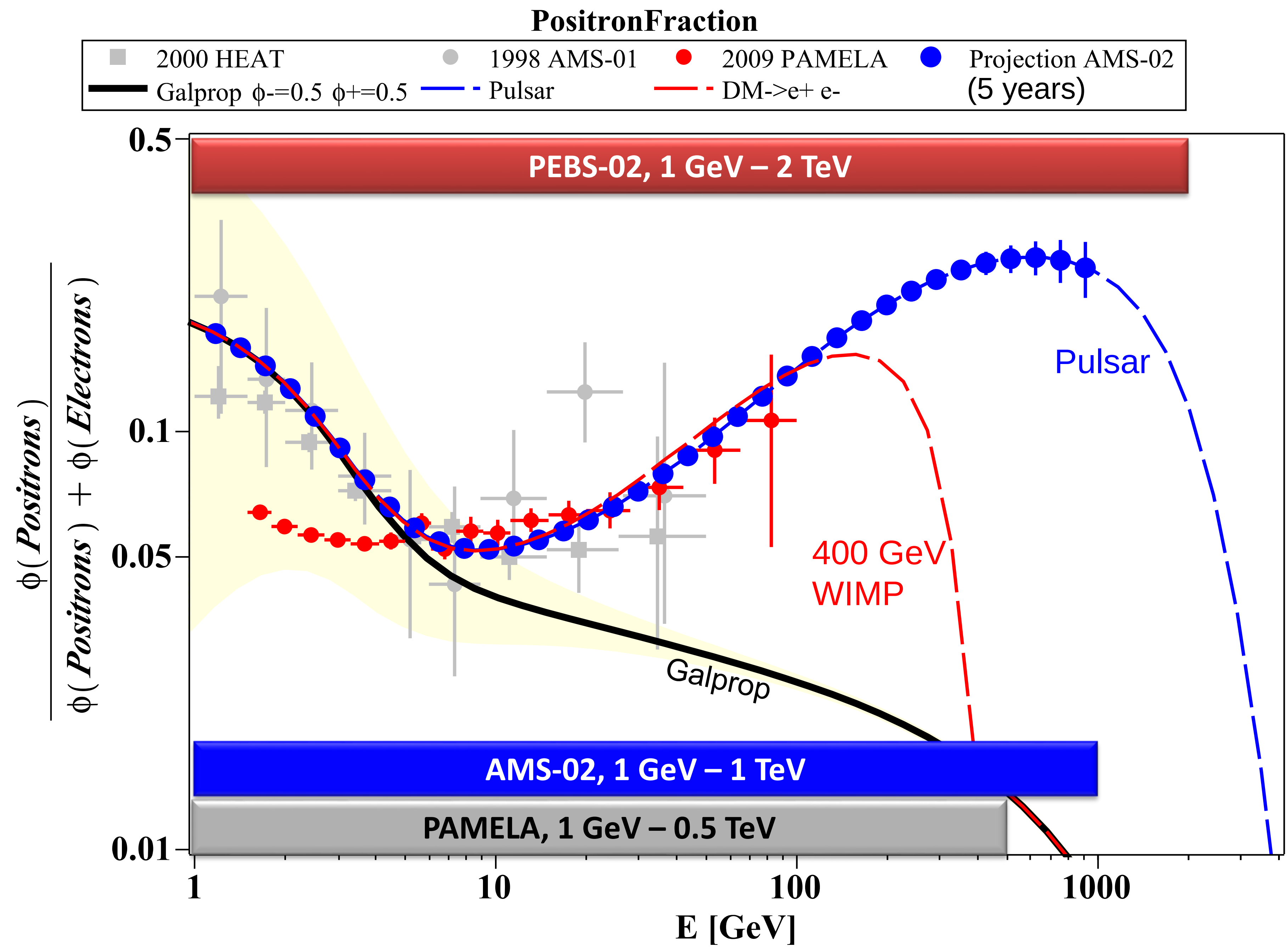
FERMI-LAT (inferred charge)



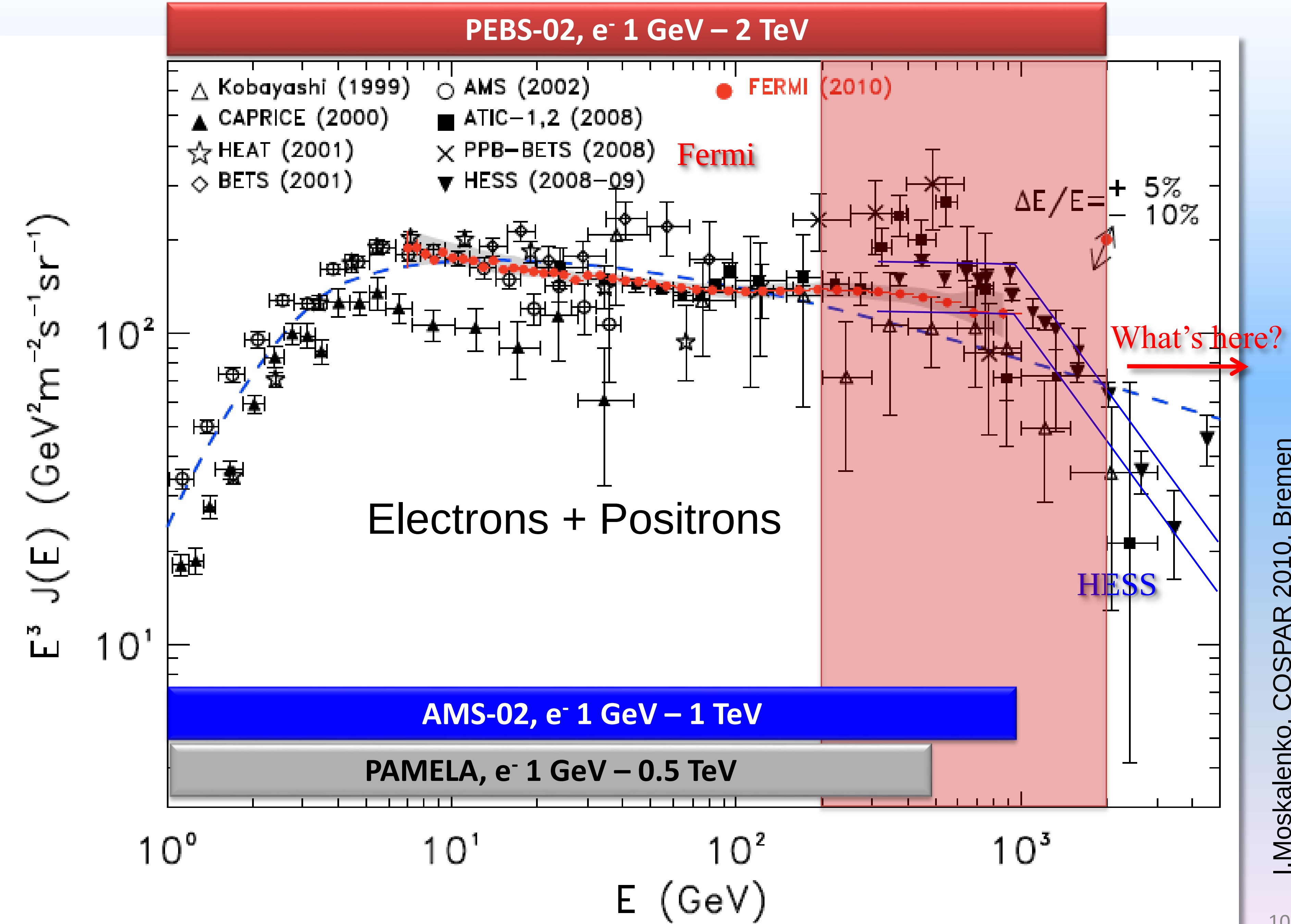
arXiv:1109.0521v1 [astro-ph.HE] 2 Sep 2011



Positron Fraction
Fraction still increasing with E
How far in energy will they go?
AMS-02
Positron fraction
10^{-1}
1
10
10^2
positron, electron energy [GeV]
AMS
FERMI
PAMELA
AMS-01
HEAT
CAPRICE98
CAPRICE94
TS93



PositronFraction
2000 HEAT
1998 AMS-01
2009 PAMELA
Projection AMS-02
(5 years)
Galprop ϕ-=0.5 ϕ+=0.5
Pulsar
DM->e+ e-
PEBS-02, 1 GeV – 2 TeV
Pulsar
400 GeV
WIMP
Galprop
AMS-02, 1 GeV – 1 TeV
PAMELA, 1 GeV – 0.5 TeV
0.5
0.1
0.05
0.01
1
10
100
1000
E [GeV]
ϕ(Positrons) / ϕ(Positrons) + ϕ(Electrons)


PEBS-02, e⁻ 1 GeV – 2 TeV
Kobayashi (1999)
CAPRICE (2000)
HEAT (2001)
BETS (2001)
AMS (2002)
ATIC−1,2 (2008)
PPB−BETS (2008)
HESS (2008−09)
FERMI (2010)
Fermi
ΔE/E= + 5% − 10%
What's here?
Electrons + Positrons
HESS
AMS-02, e⁻ 1 GeV – 1 TeV
PAMELA, e⁻ 1 GeV – 0.5 TeV
E^3 J(E) ($GeV^2m^{-2}s^{-1}sr^{-1}$)
E (GeV)
I.Moskalenko, COSPAR 2010, Bremen

Why balloons?

- Upgrades for cosmic ray space experiments are difficult
- Superconducting magnets are always more difficult than originally anticipated (AMS, LHC, ...).
  BESS is a rare exception – access is important…
- To connect cosmic ray experiments with manned space flights is a large risk (AMS 1998→2011).
- With the AMS-02 total cost of ~1500 Million $ (without Shuttle launch) one could have performed ~150 LDB Balloon experiments in the mean time.
- LDB and hopefully soon ULDB balloon flights offer an ideal and flexible platform for cosmic ray experiments for the coming decade

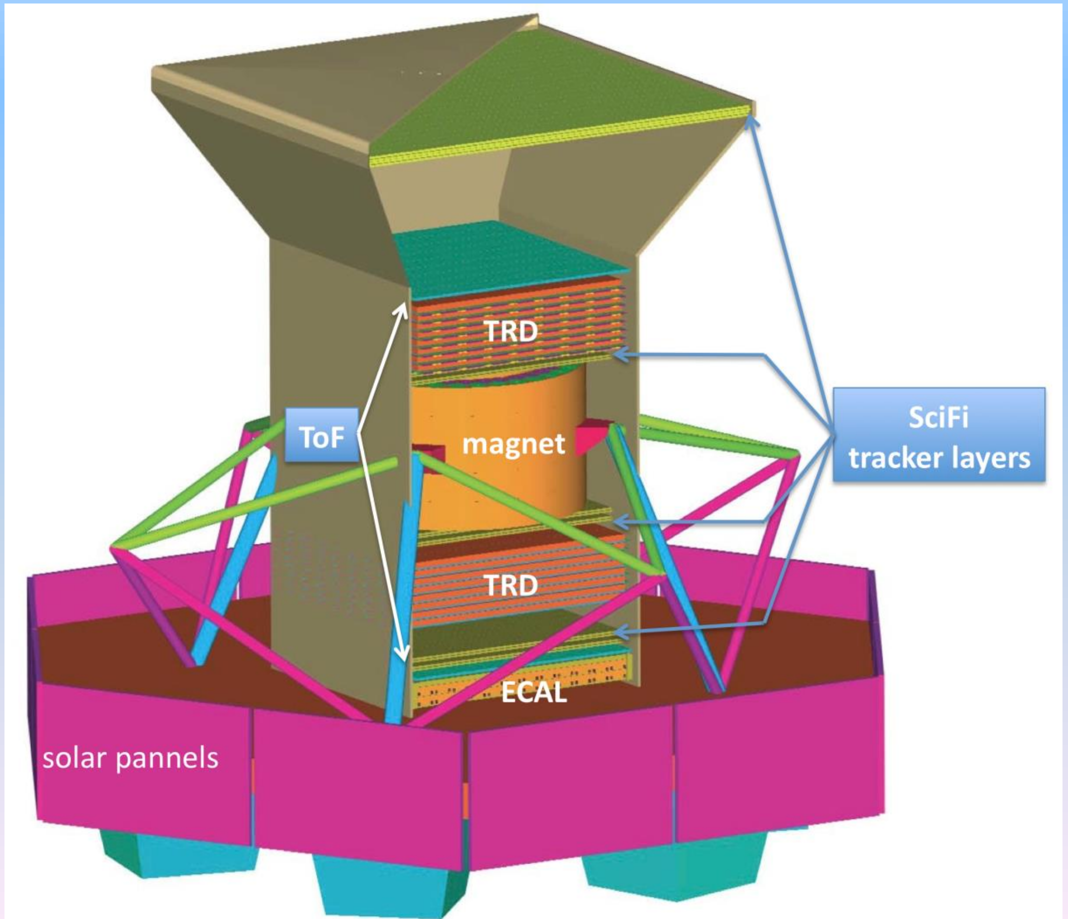
The (ex)PEBS Collaboration

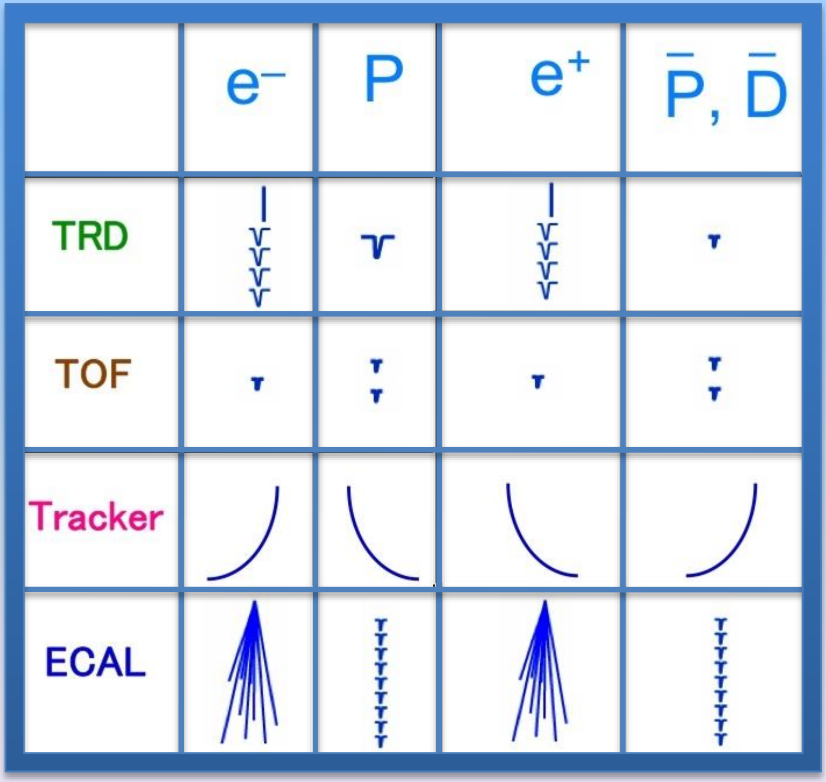
- Aachen, ETHZ and US groups submitted a proposal to NASA twice (2009, 2010)
- Rated excellent, but no funds available
- Hardware and people available nationally
- Prototype work continuing
- Looking for new collaborators/flight options…

People:
G. Dissertori, W. Lustermann, A. Howard, C. Casella
T. Nakada, G. Haffeli, J-B Mosset, L. Shchutska
S. Schael, R. Greim, V. Mikhalev…

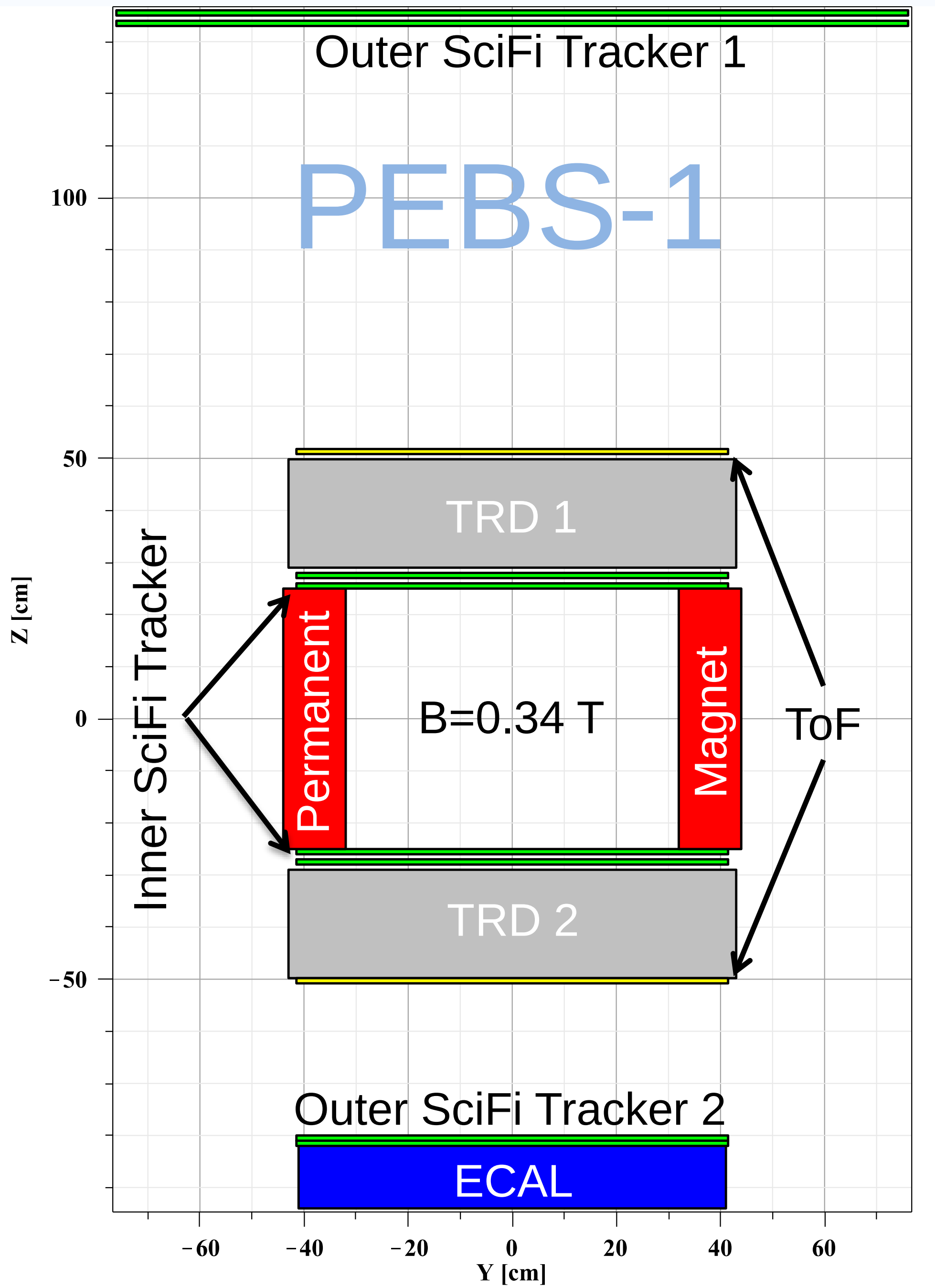
PEBS Experiment

The overall height, including the lower crush pads, is 2.7 m and the overall width is 3.3 m. The total weight of the instrument is 2000 kg.





$$\frac{\sigma_p}{p} = 0.0010 \cdot p \oplus 0.038$$

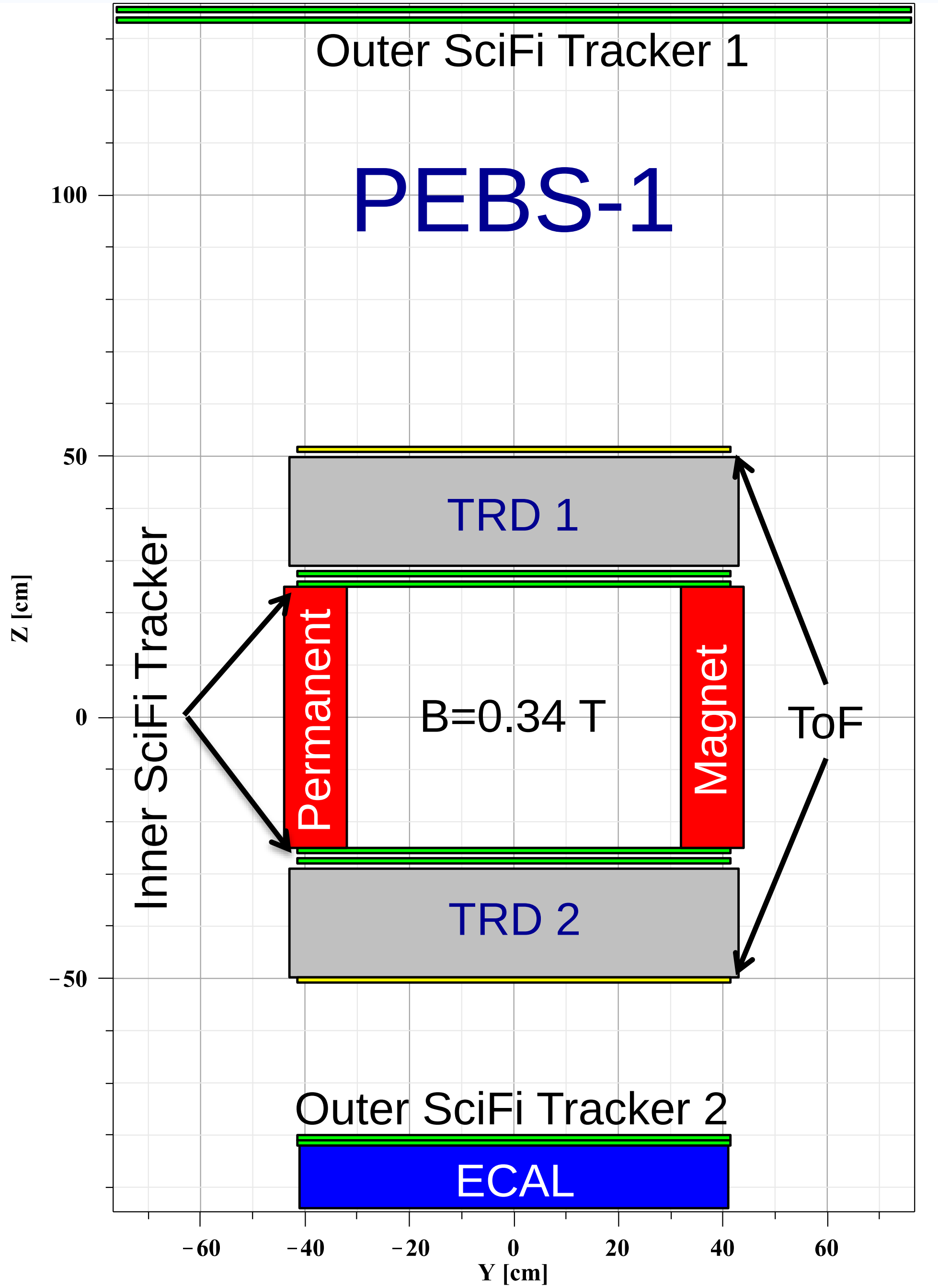


The magnetic spectrometer has a geometrical acceptance of 1200 cm^2 sr for electrons.

The most important contributions to the overall weight are the magnet (890 kg) and the calorimeter (650 kg),

The power consumption is dominated by the 250 W needed for the tracker which has roughly 60,000 individual readout channels.

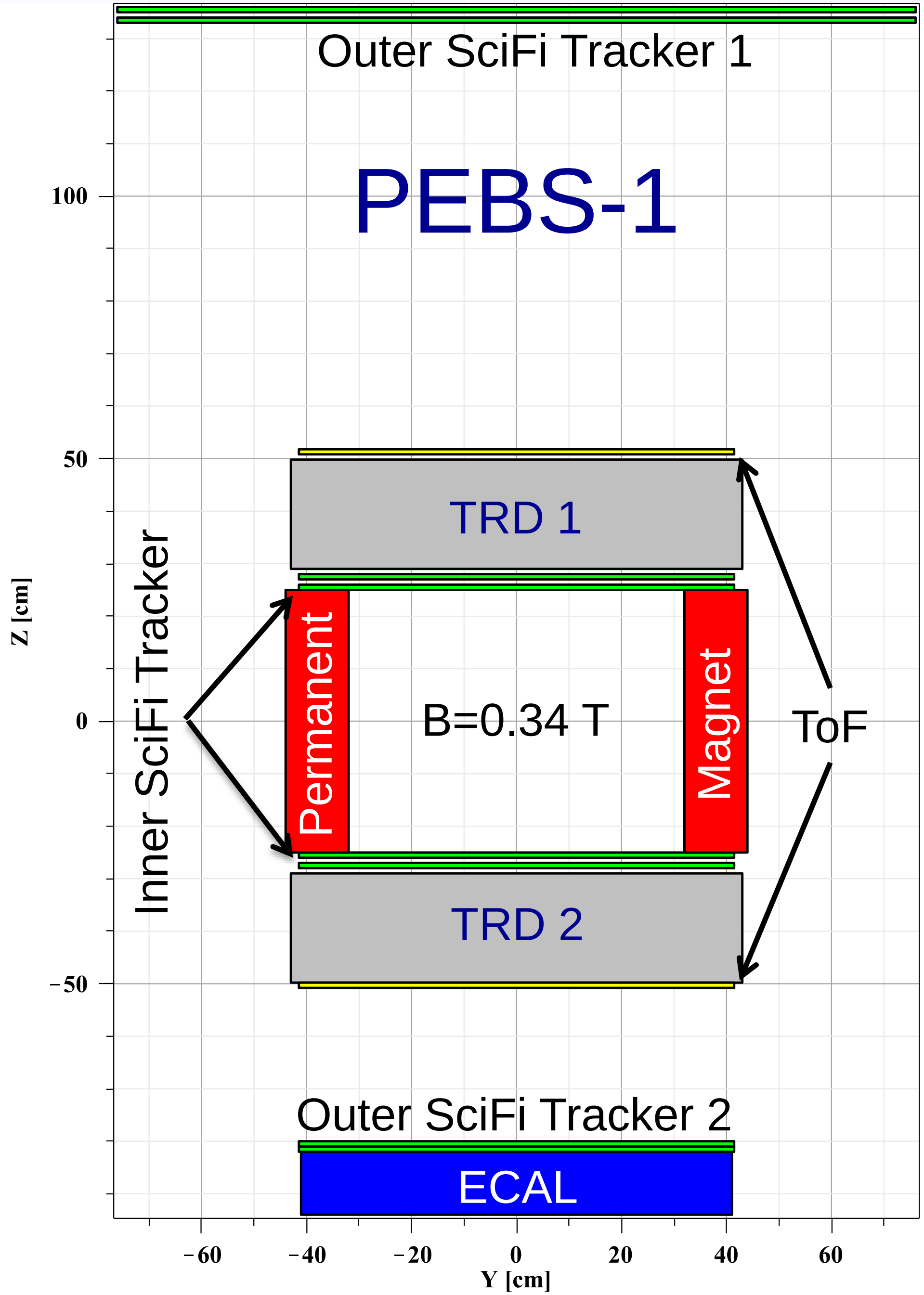
The lower detector combination of TRD and ECAL, which can be used for the measurement of the combined electron-positron spectrum at high energies, has an acceptance of 6000 cm^2 sr.



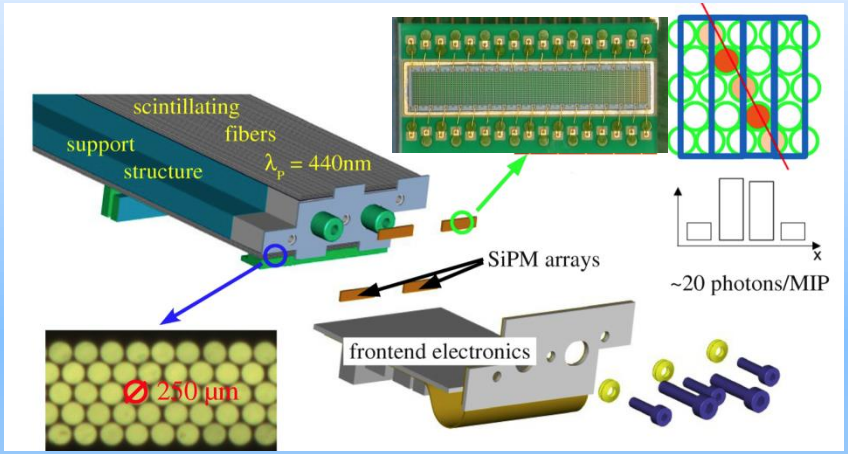
This detector concept can be used as a multi purpose platform for the study of cosmic rays.

Use the flexibility of Balloon Experimentes to:

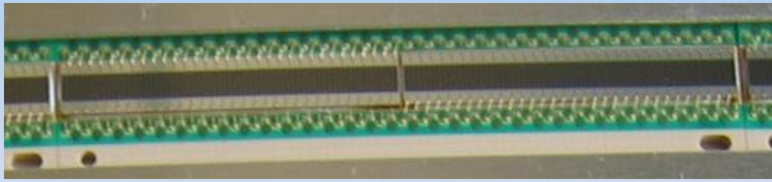
1. optimize the detector for different physics topics
2. continously upgrade the detector performance



Upgrade the SciFi Tracker

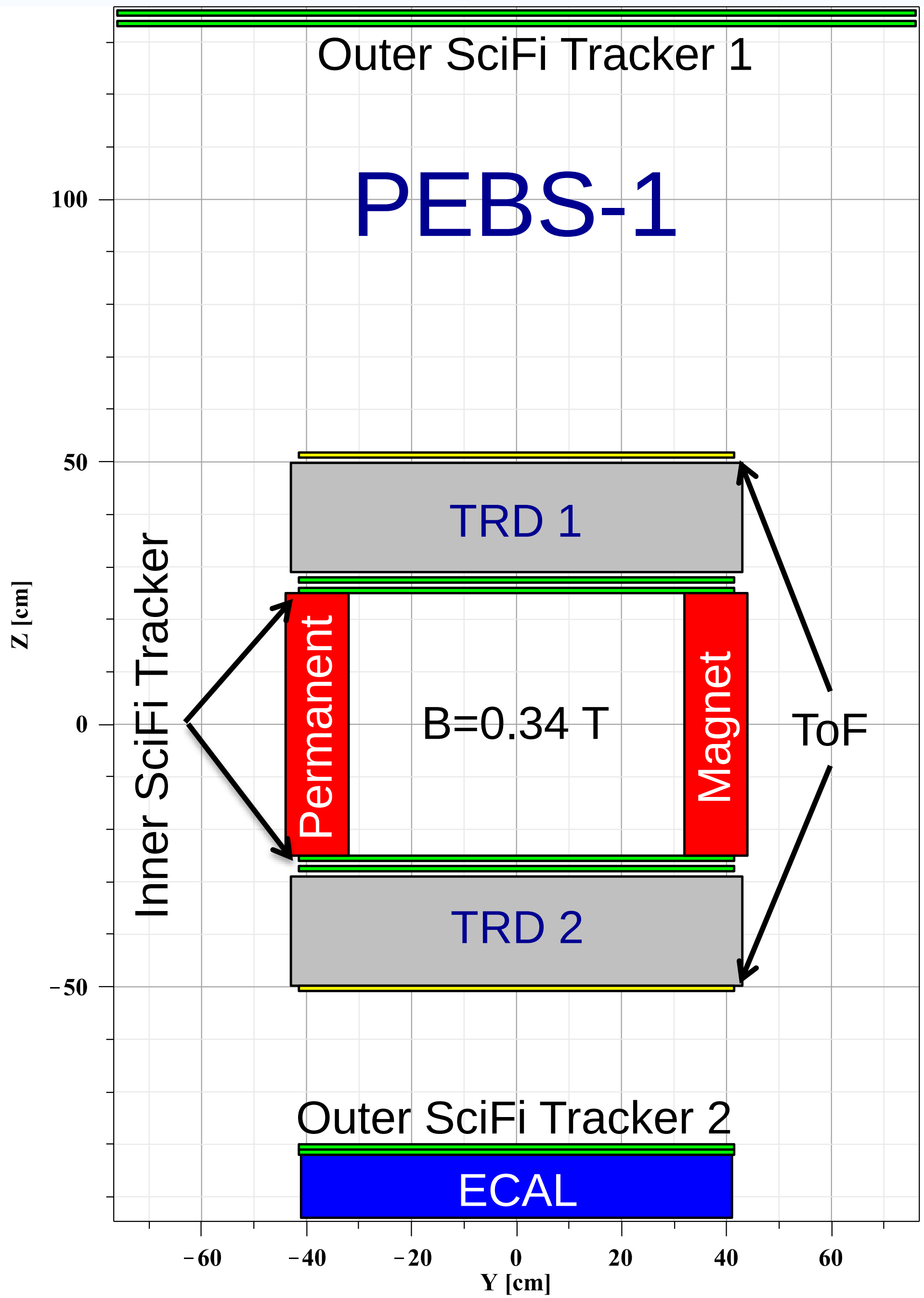


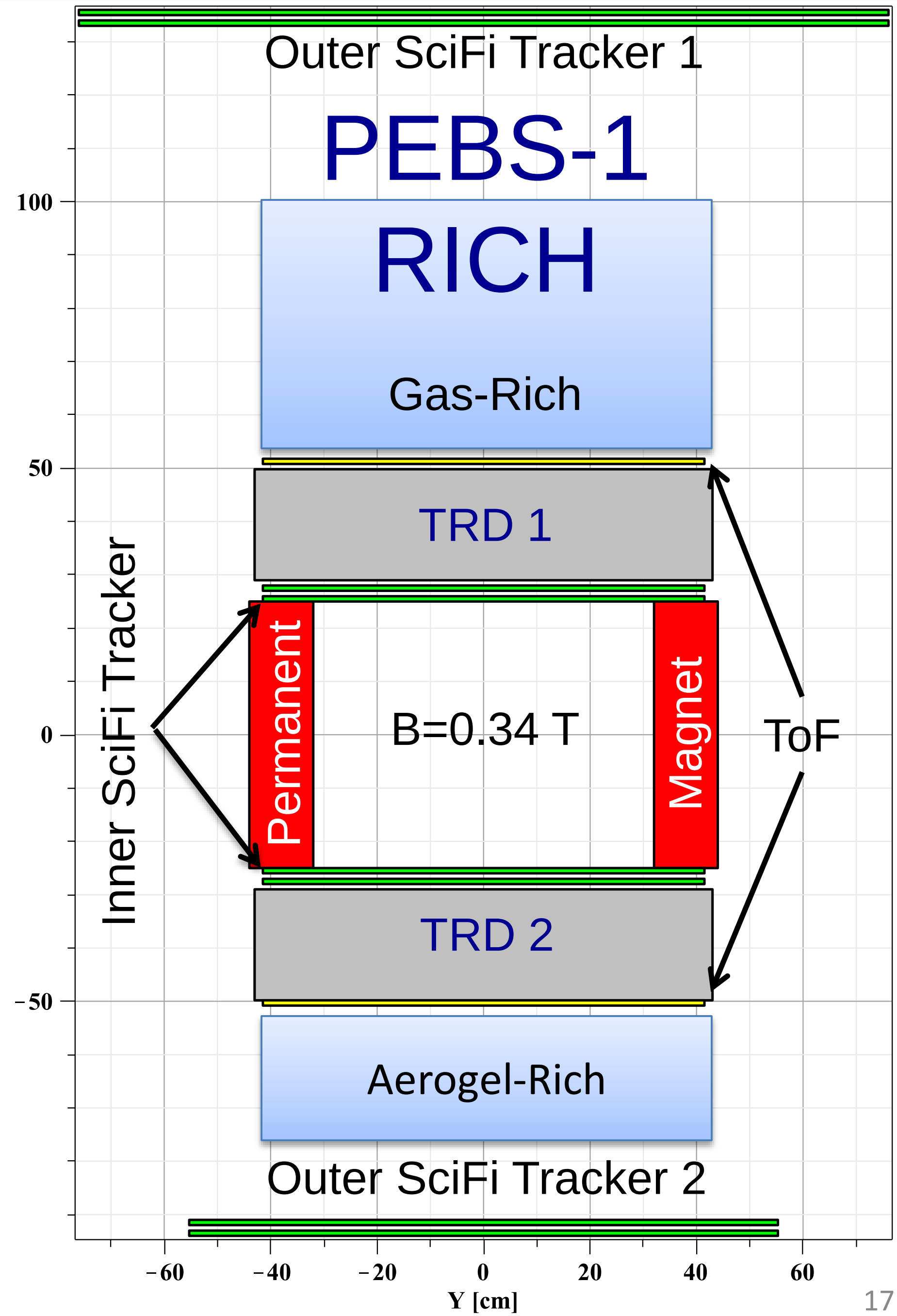
1. Readout the fibers on both ends

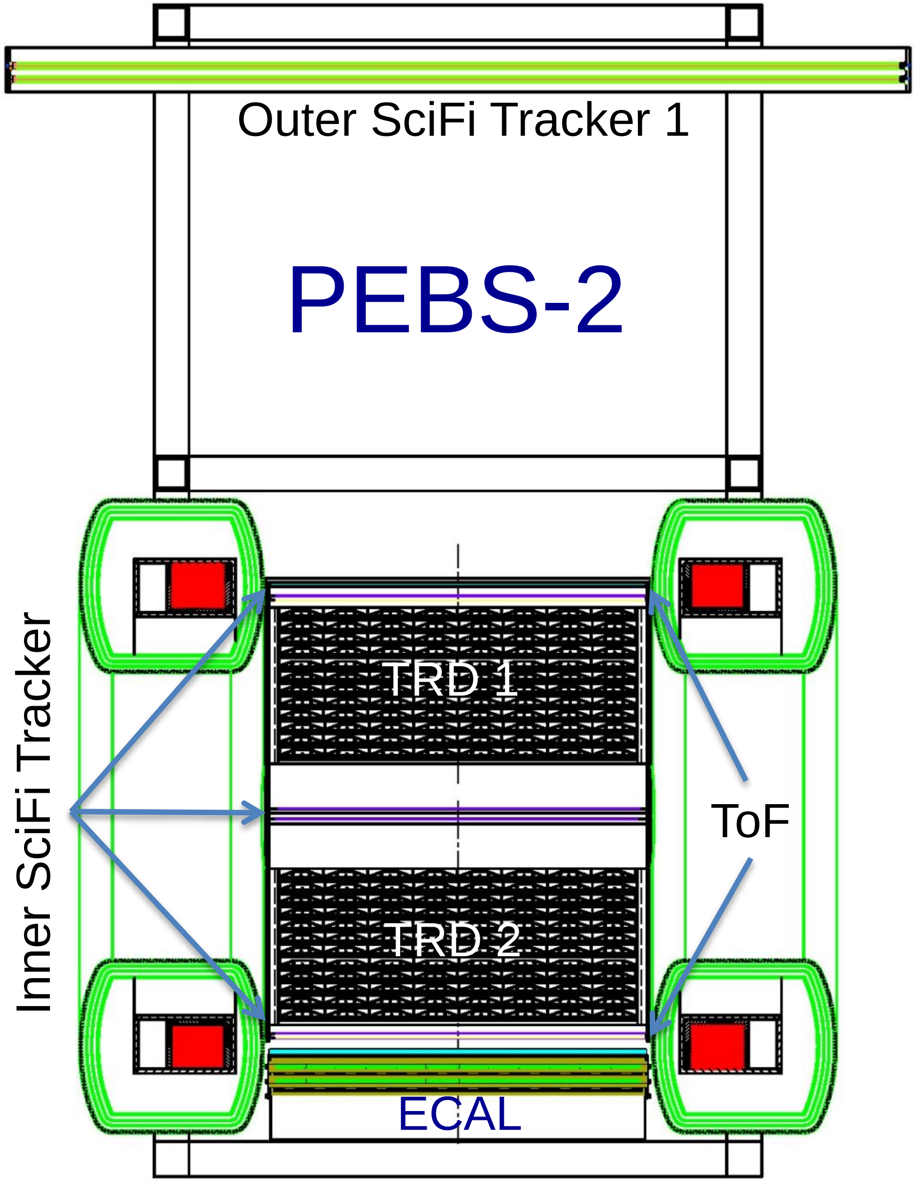


2. Reduce the readout pitch from 0.25 mm ➔0.125 mm

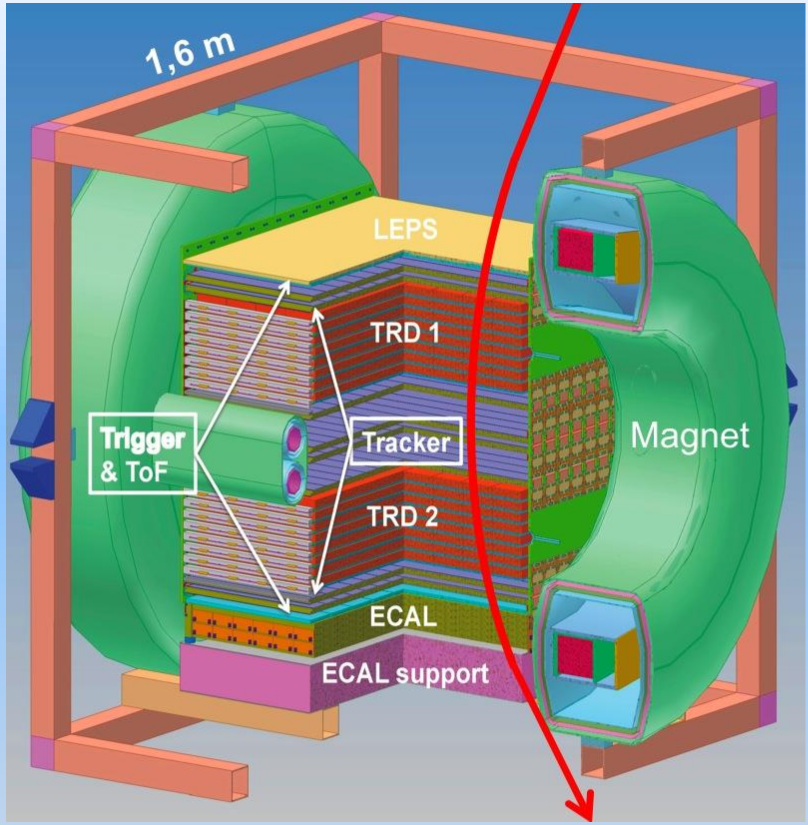
MDR 1 TeV ➔ 2 TeV


Outer SciFi Tracker 1
PEBS-1
TRD 1
Inner SciFi Tracker
Permanent
B=0.34 T
Magnet
ToF
TRD 2
Outer SciFi Tracker 2
ECAL
Z [cm]
Y [cm]
100
50
0
−50
−60
−40
−20
0
20
40
60


Outer SciFi Tracker 1
PEBS-1
RICH
Gas-Rich
TRD 1
Inner SciFi Tracker
Permanent
B=0.34 T
Magnet
ToF
TRD 2
Aerogel-Rich
Outer SciFi Tracker 2
Y [cm]
100
50
0
−50
−60
−40
−20
0
20
40
60



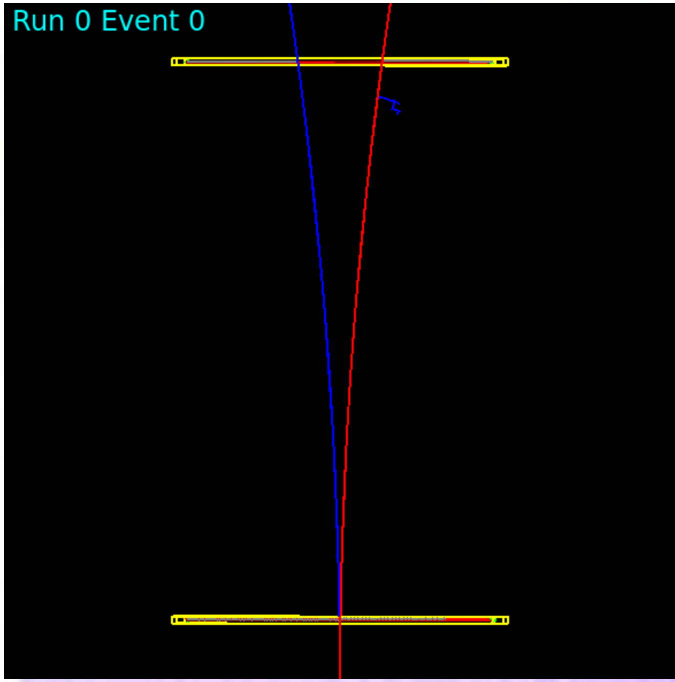
Upgrade the Magnet

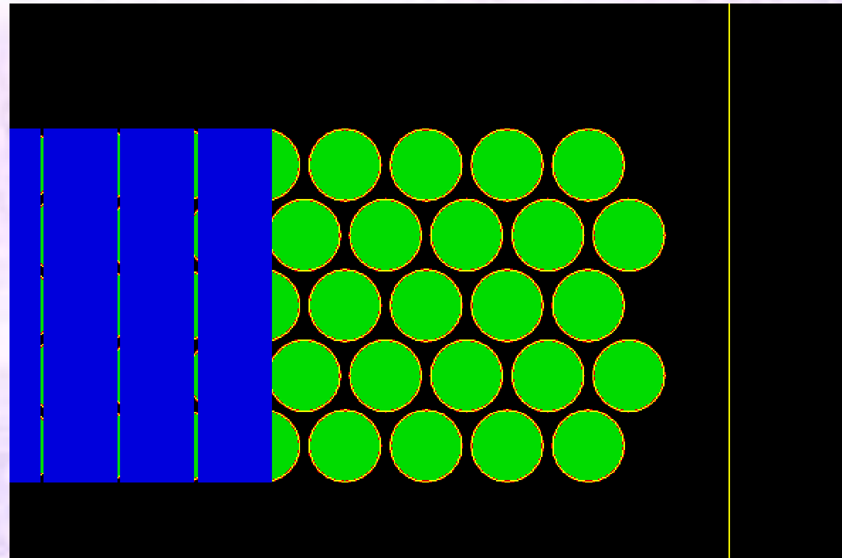


Replace the permanent magnet with a superconducting magnet

B-field:	0.34 T	→ 0.9 T
MDR:	1 TeV	→ 4 TeV
Acceptance:	0.12 m^2sr	→ 0.25 m^2sr
Cost:	0.2 M$	→ 2 M$

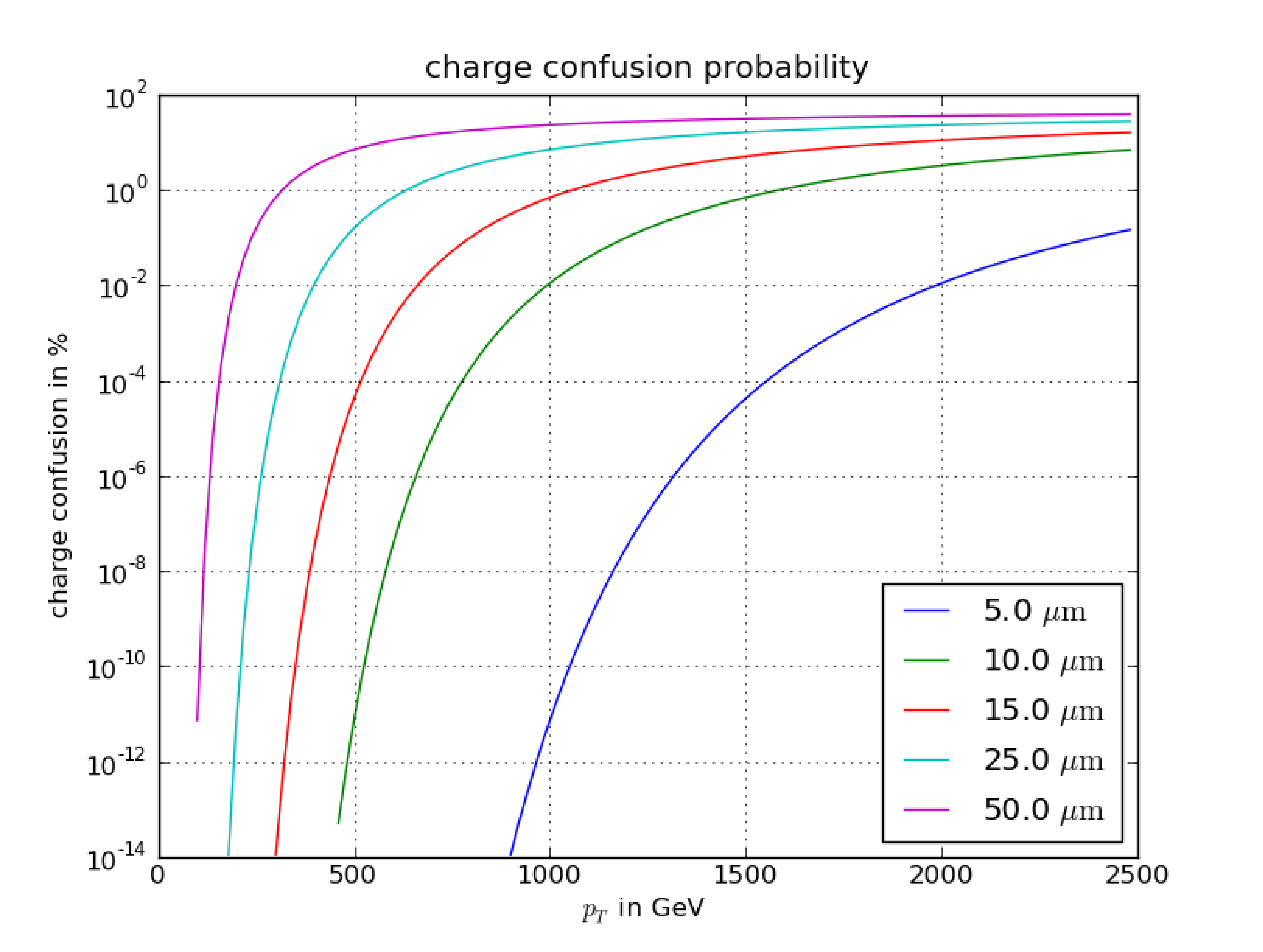
Detector Performance





- **Tracker, magnet, TRD→ 10^3 proton rejection**
- **ECAL → 10^3 proton rejection at high energy**
- **Superconducting magnet – Charge measurement > TeV (positron/electron)**

Silicon tracker?

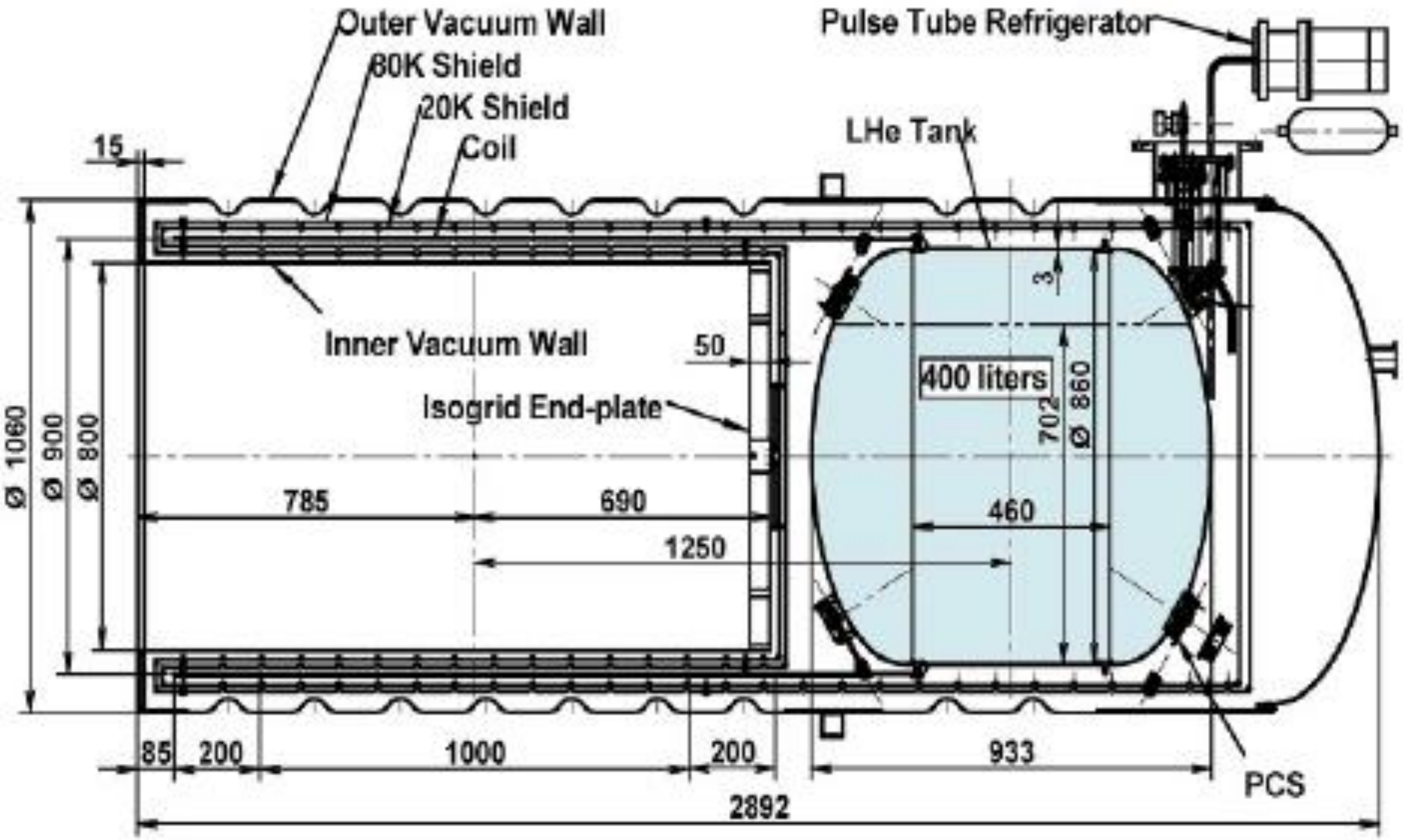


BESS Magnets?

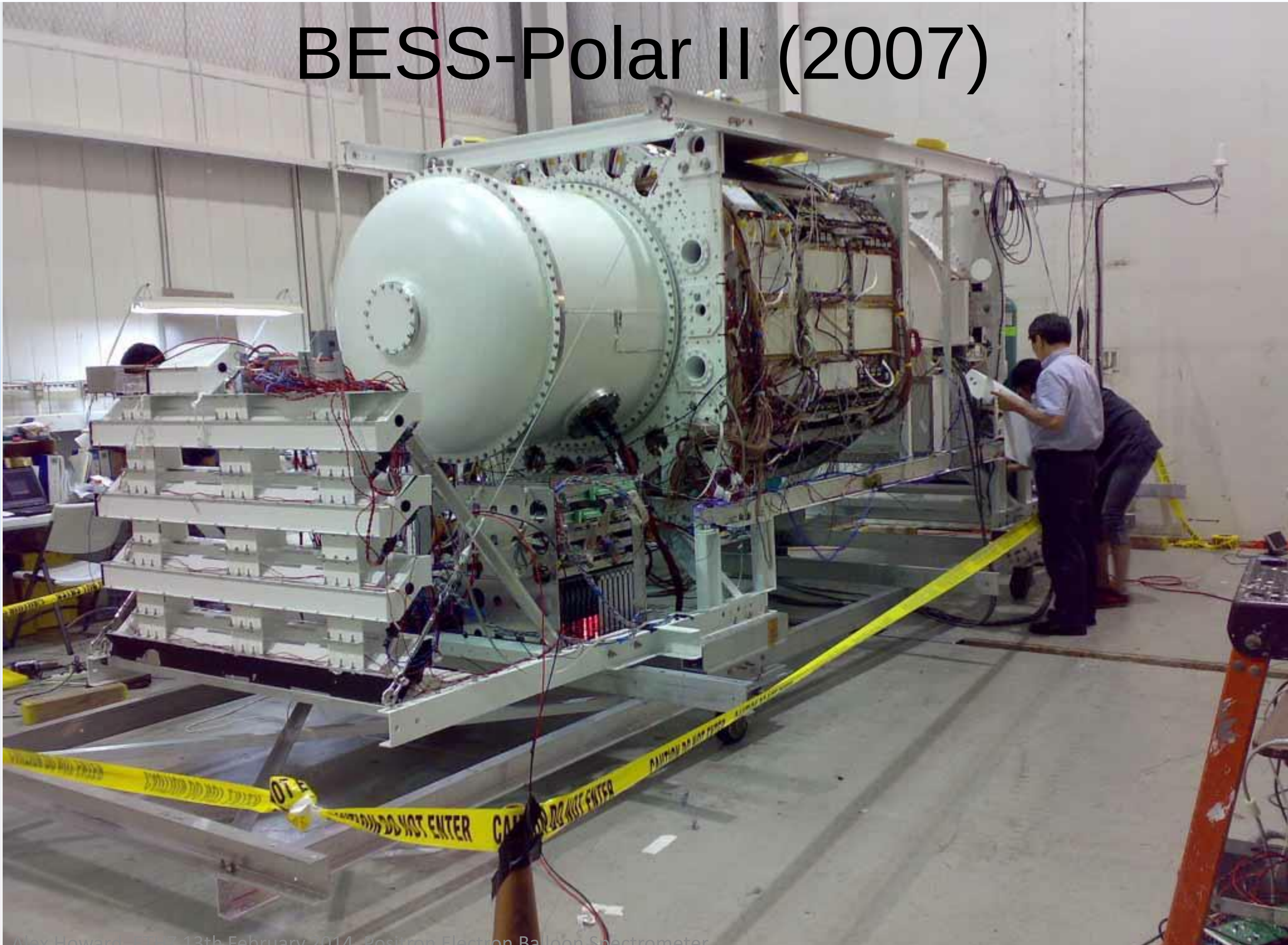
Magnet for Balloon-borne experiment

- BESS/Super Jacee type 4
  - 1 Tesla
  - Radiation length ~ 0.2 X_0
  - Life ~ 5 days
- BESS-Polar type 2
  - 0.8 Tesla
  - Radiation length < 0.1 X_0
  - Life ~ 30 days

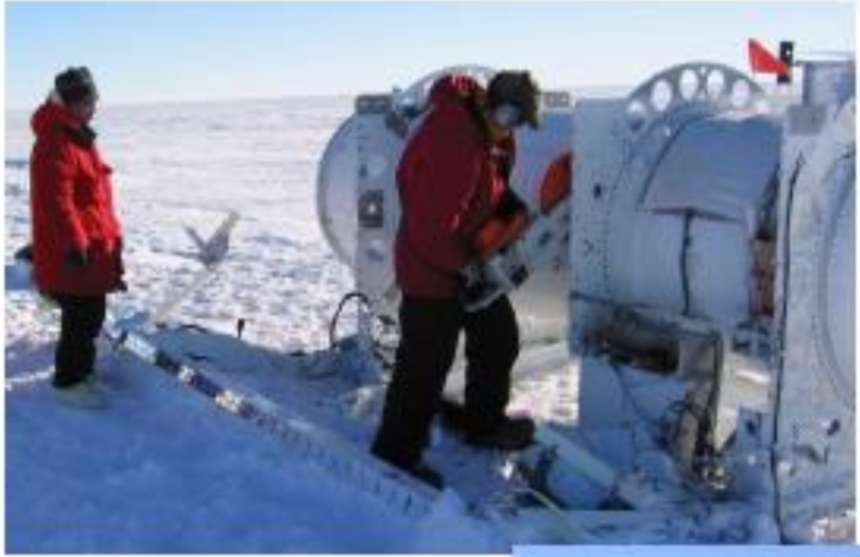
BESS-Polar Magnet



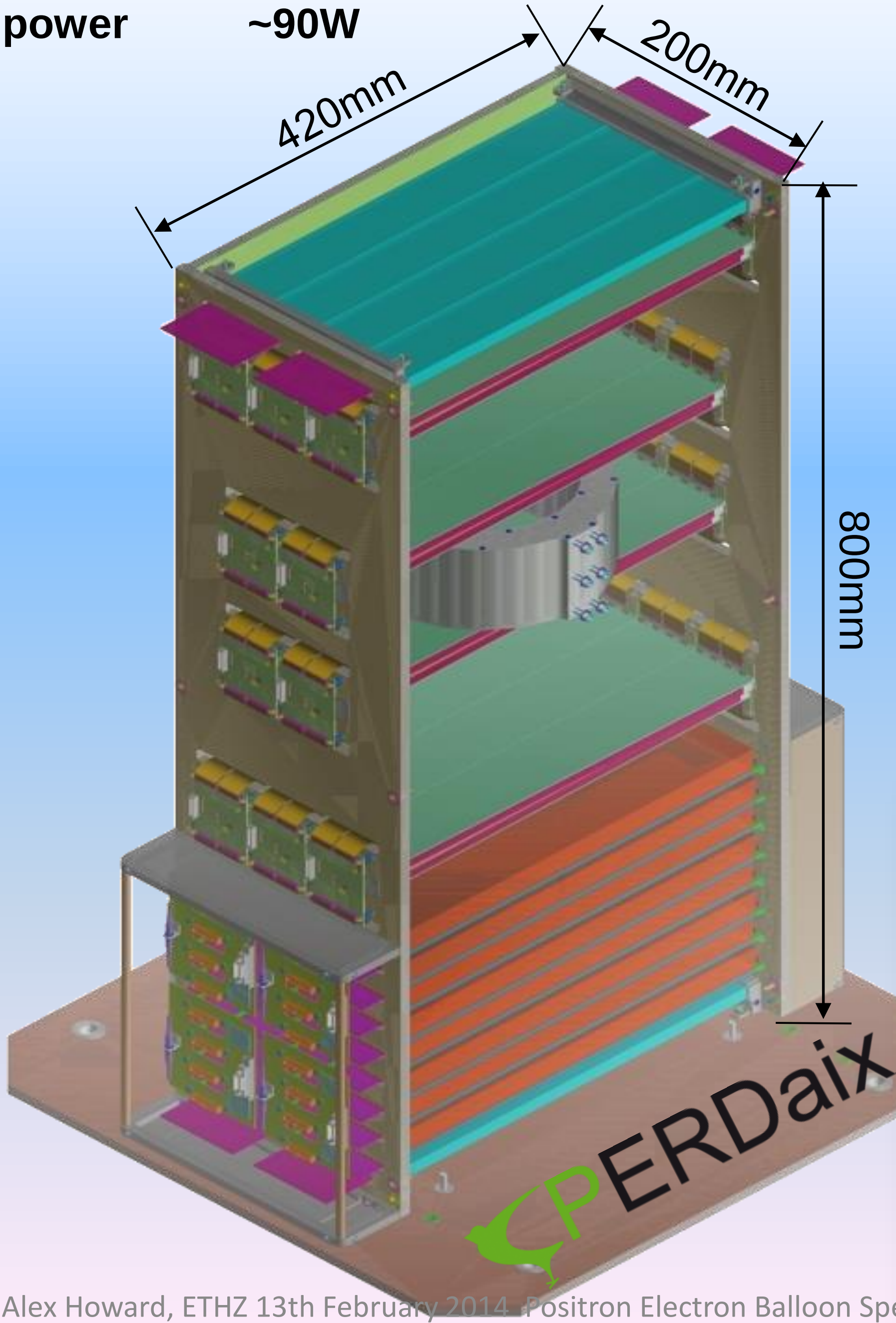
BESS-Polar II (2007)



Fate of BESS-Polar I

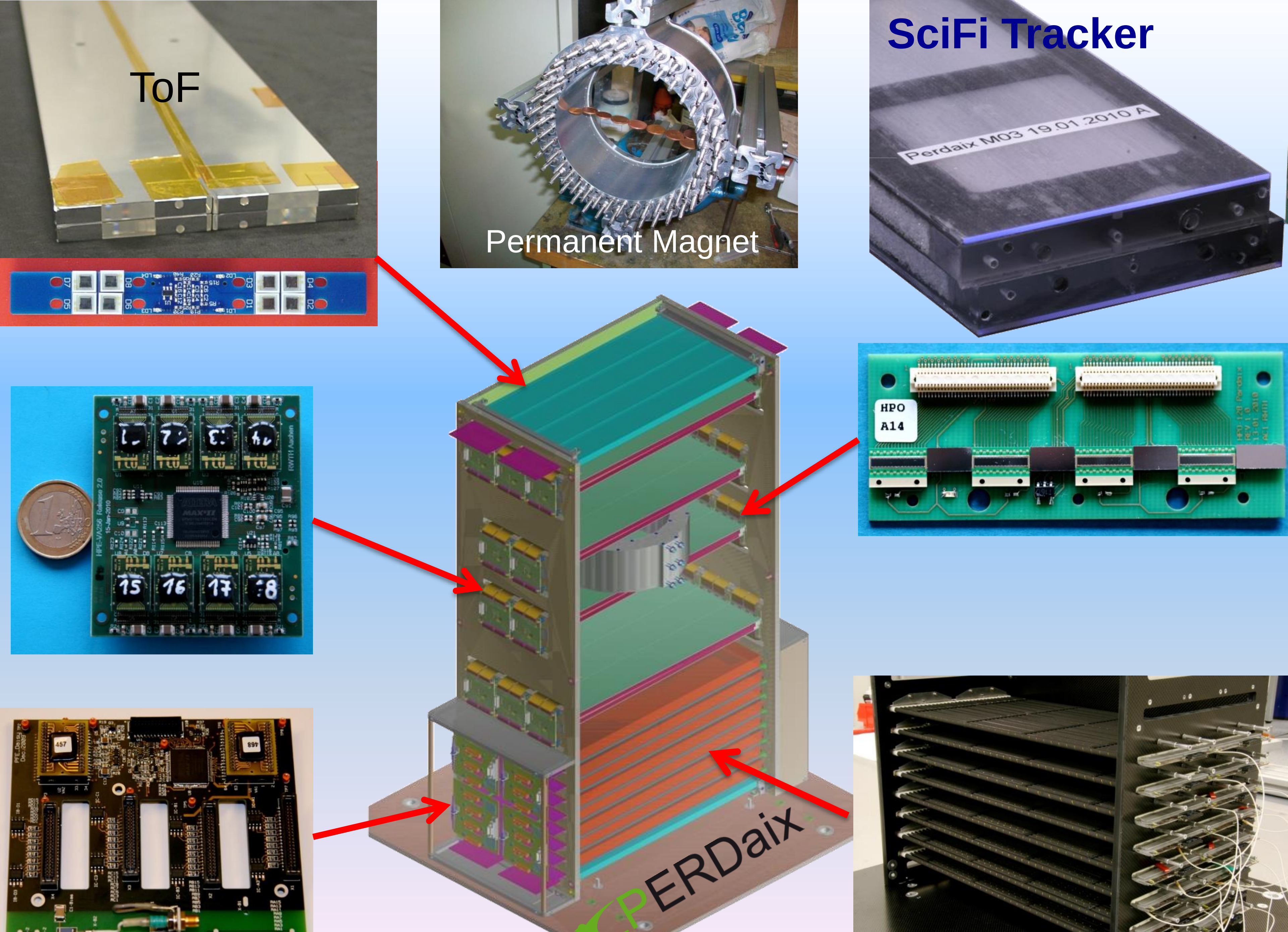


Acceptance ~40 cm²sr
weight ~40kg
power ~90W

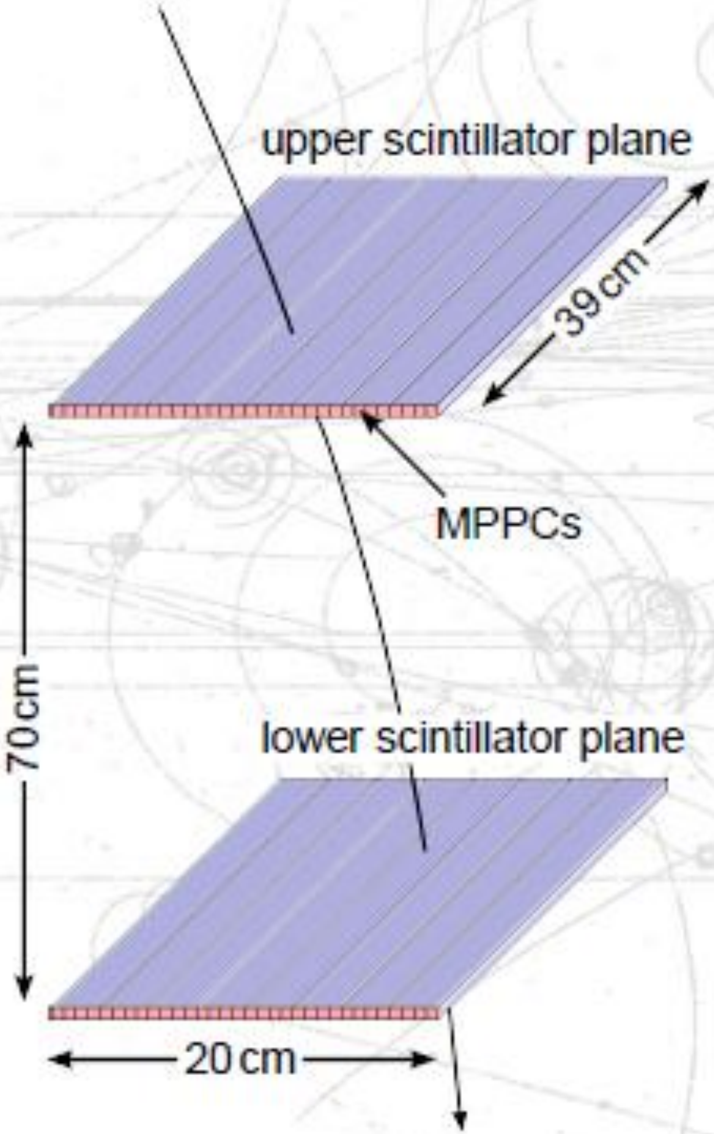


PEBS Prototype: PERDaix

- Proton Electron Radiation Detector Aix-La-Chapelle
- Balloon-borne spectrometer
- Measurement of cosmic rays up to 5 GeV
- First successfull balloon flight in October 2010


ToF
Permanent Magnet
SciFi Tracker
Perdaix M03 19.01.2010 A
HPO
A14
PERDaix

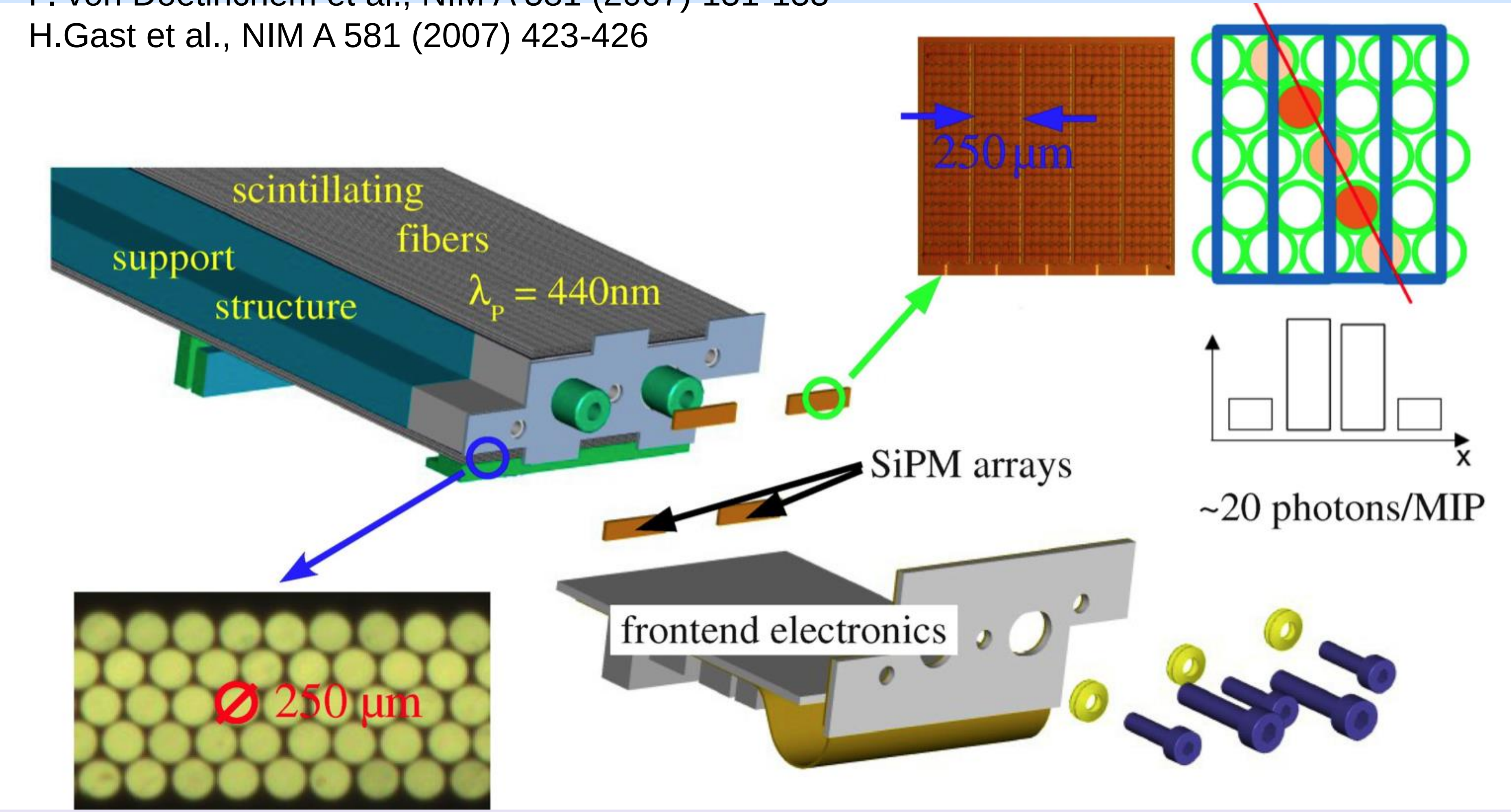
Time of Flight System



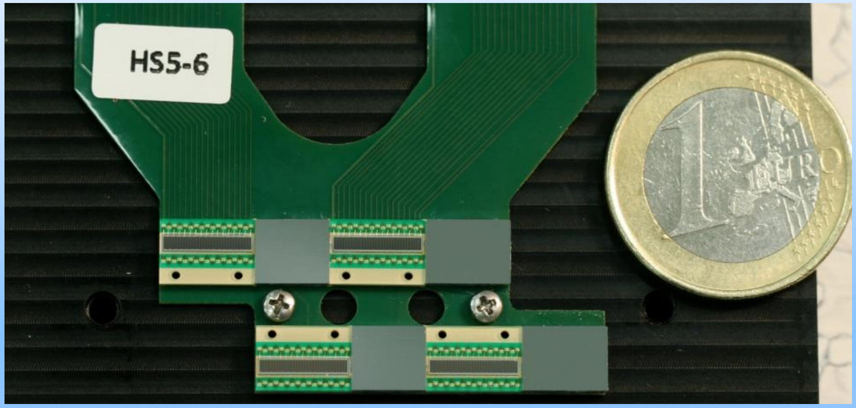
- 2 layers of 8 scintillator bars each read out by silicon photomultipliers
  - main trigger
  - reject upward flying particles
  - measure particle velocity
  - → identify heavy particles
- 300 ps design time resolution
- proton rejection up to 1.5 GeV

PEBS Scintillating Fiber Tracker

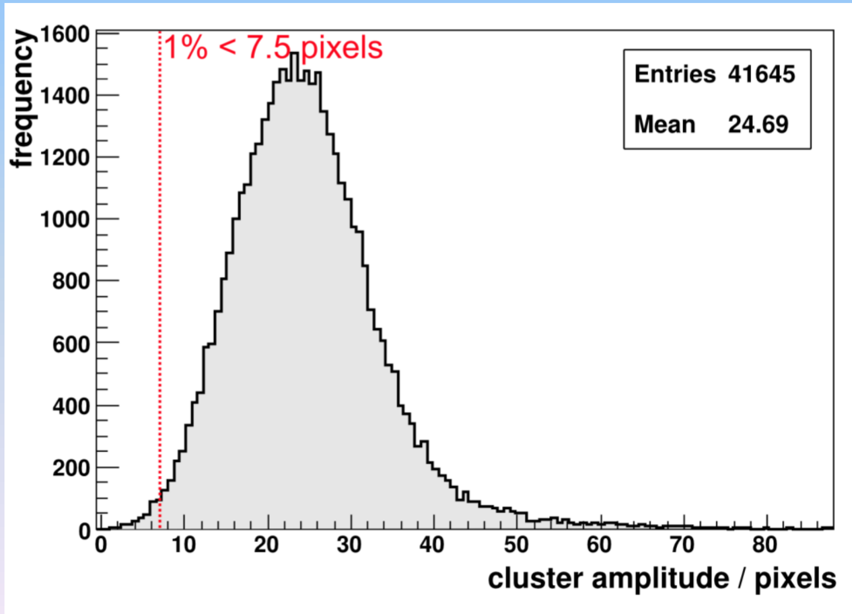
P. von Doetinchem et al., NIM A 581 (2007) 151-155
H.Gast et al., NIM A 581 (2007) 423-426



Testbeam 2009: Position Resolution 0.05 mm

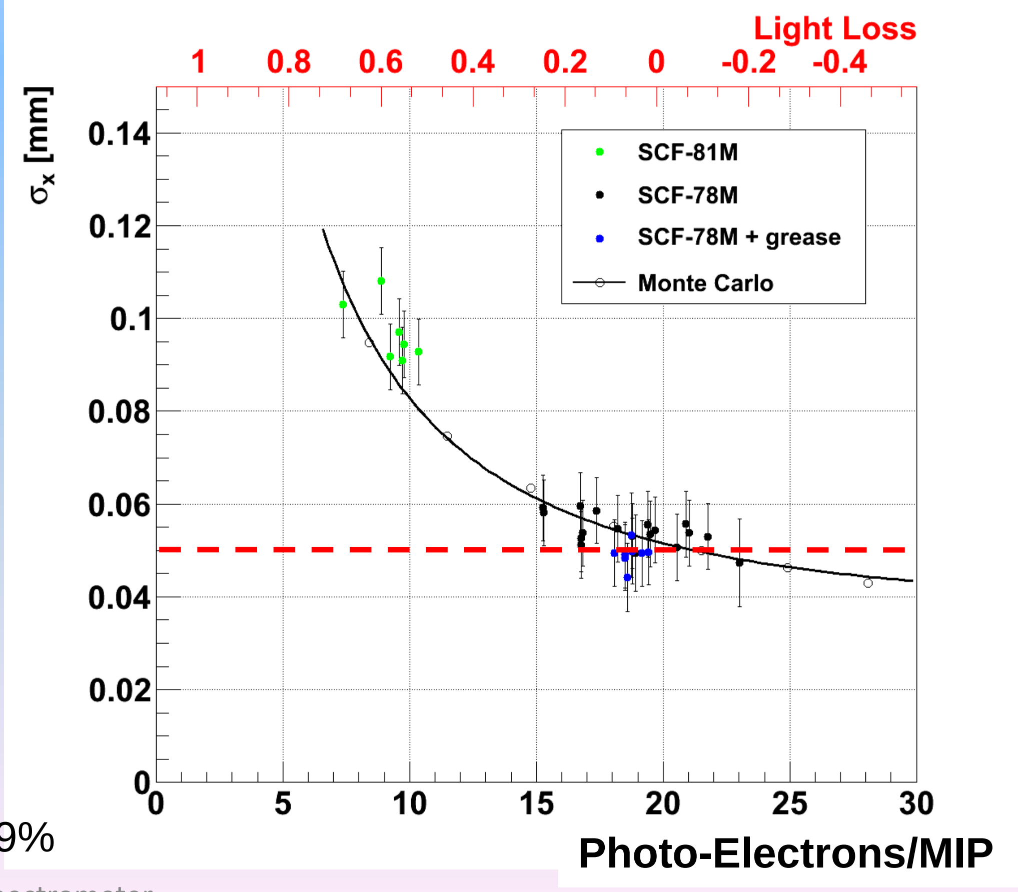


Optical front end hybrid for the SciFi Tracker

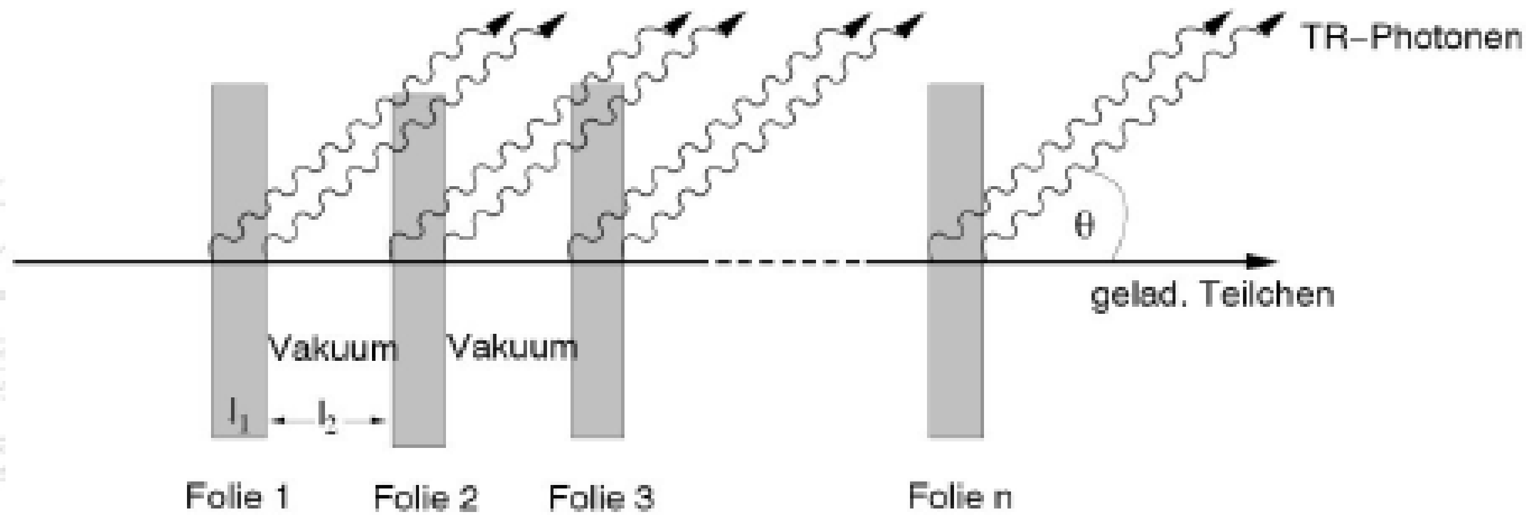


Light yield for a MIP => tracking efficiency > 99%

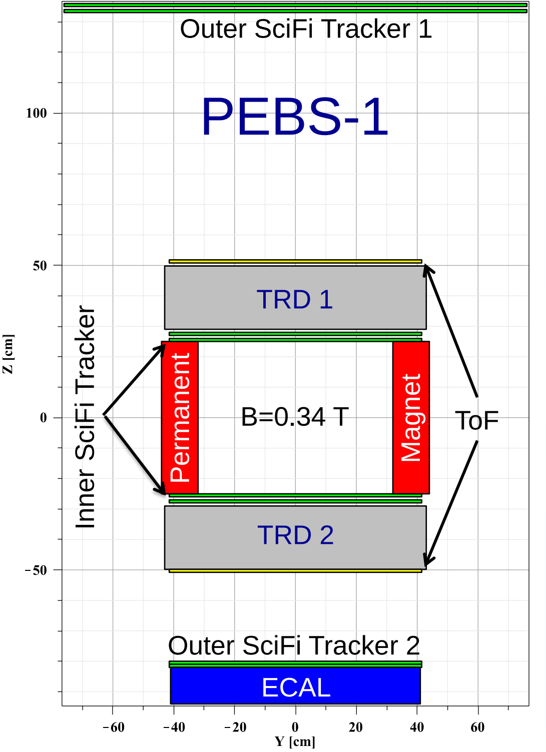
Comparision of position resolution and light yield from 2009 test beam data with the Monte Carlo Simulation for different Kuraray fibers.



Transition Radiation Detector



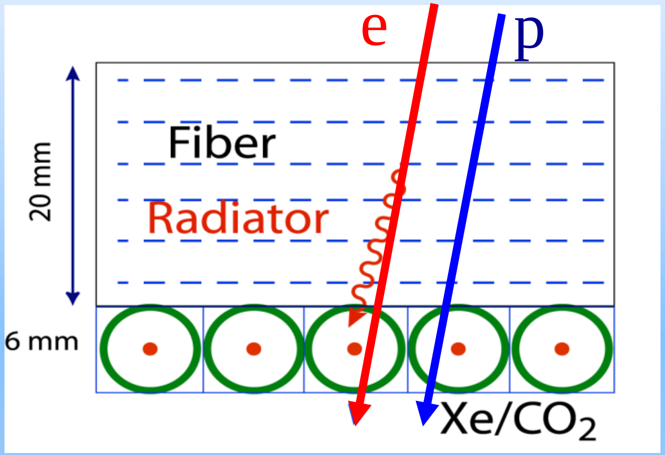
- Charged particles crossing the interface between two media with different indices of refraction produce so-called transition radiation.
  - the energy of the TR-Photons increases with particle velocity
  - once the particle momentum reaches 1000 times the particle mass, TR-photons are produced in the X-Ray spectrum
- The production threshold energies for X-Ray TR-Photons are:
  - ~0.5 GeV for electrons
  - ~100 GeV for muons (the next heavier particle found in cosmic rays)
  - ~1000 GeV for protons

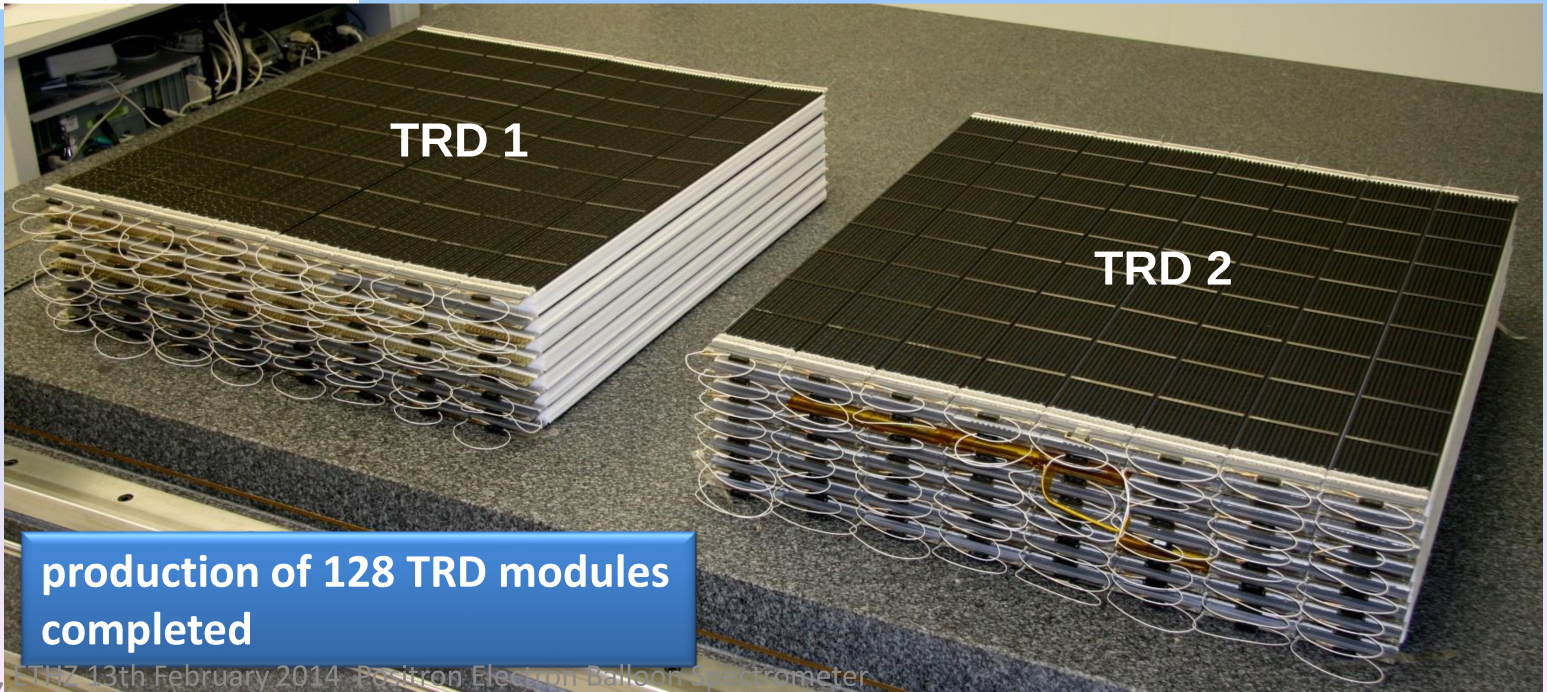


PEBS TRD

2x8 Layers each existing of:

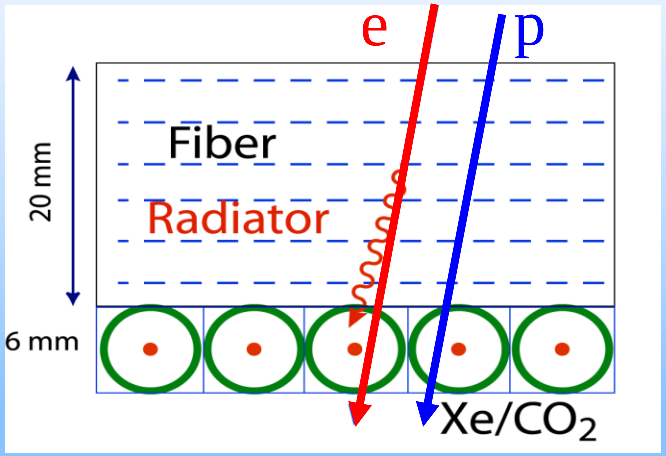
- **20 mm fibre fleece**
- **Ø 6 mm straw tubes filled with Xe/CO_2 80%/20%**
- **HV 1450 V**

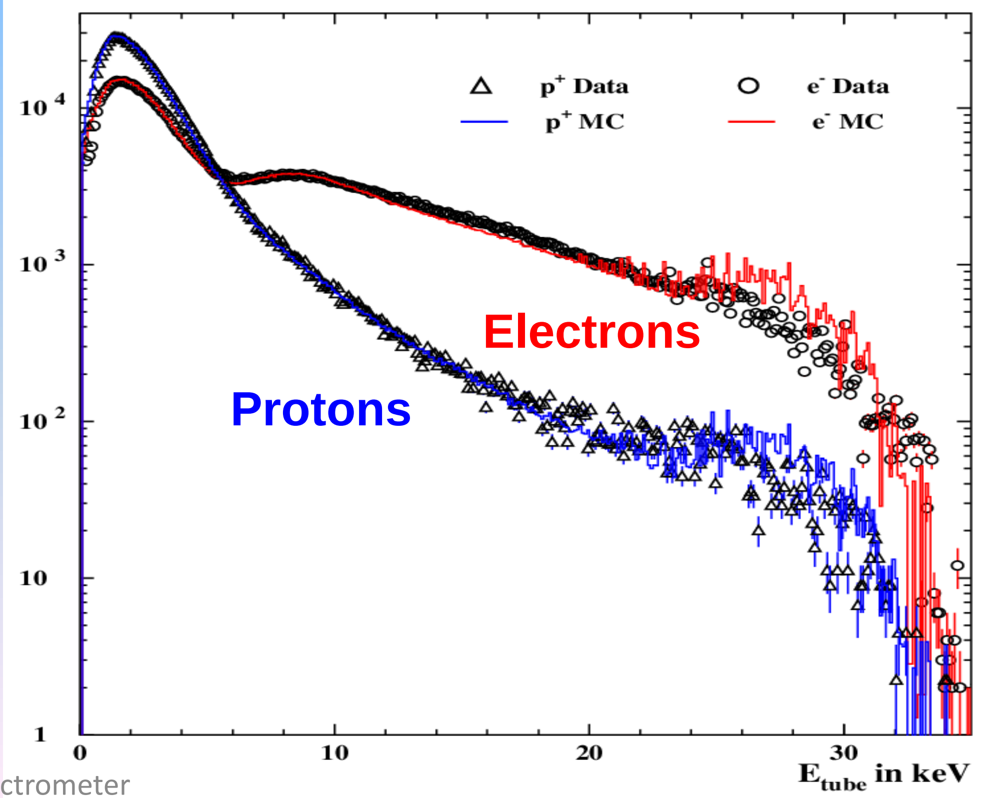


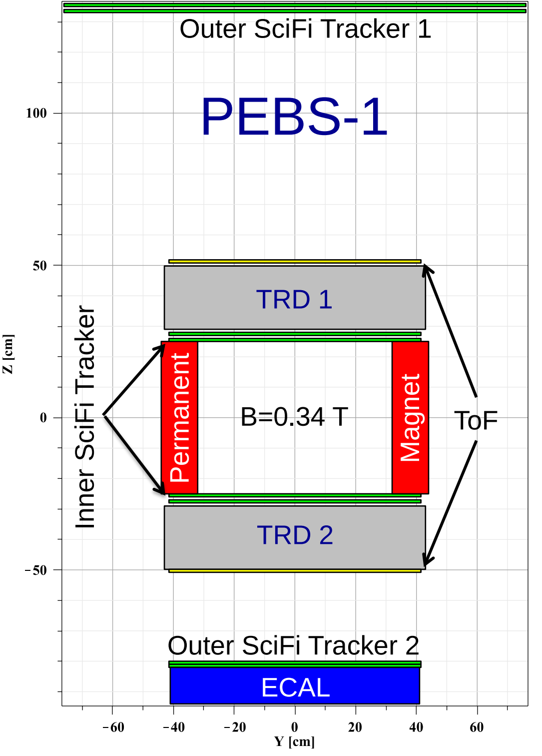


production of 128 TRD modules completed

TRD Qualification & Performance







PEBS ECAL

sandwich calorimeter for 3D-shower reconstruction

20 layers in total:

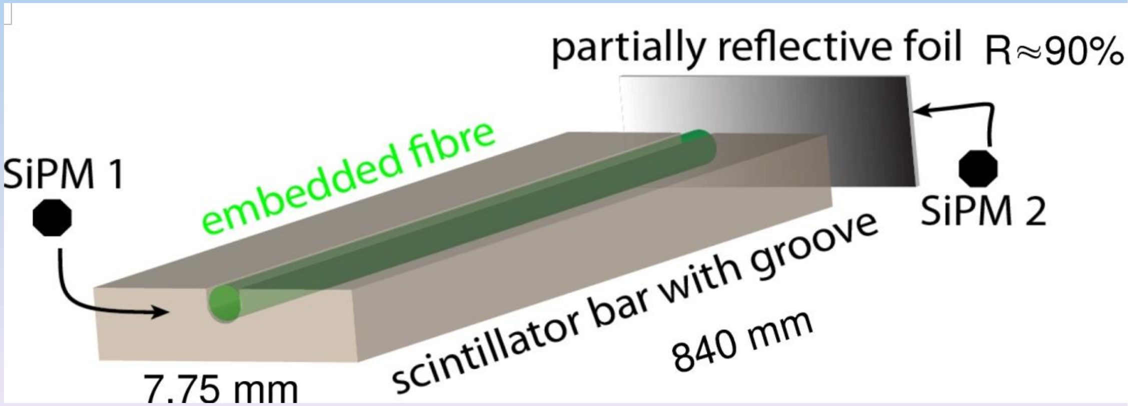
2 mm tungsten +

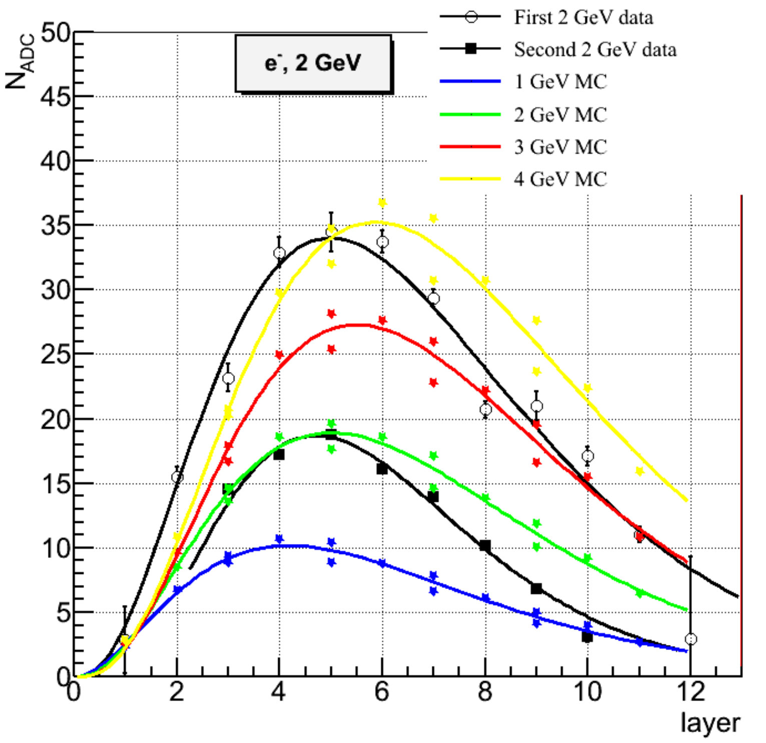
2 mm scintillator bar + WLS fiber +

2 SiPMs

11.4 X_0 in total

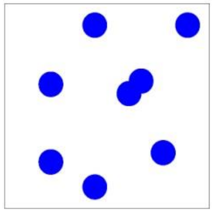
Test-Beam 2009



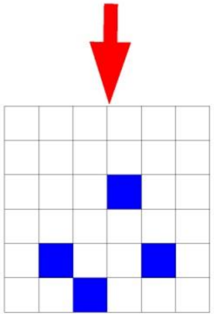


ECAL dynamic range

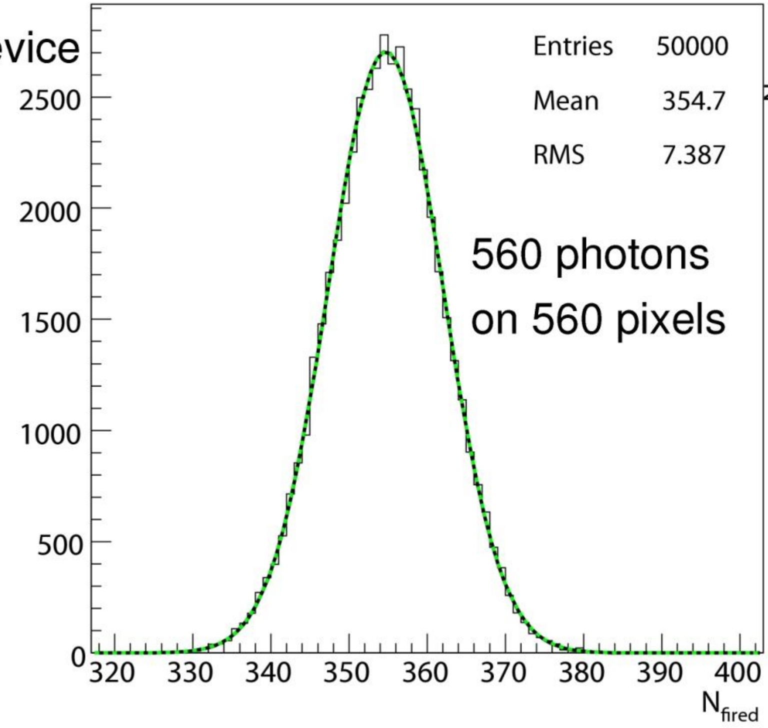
SiPM is pixellated device

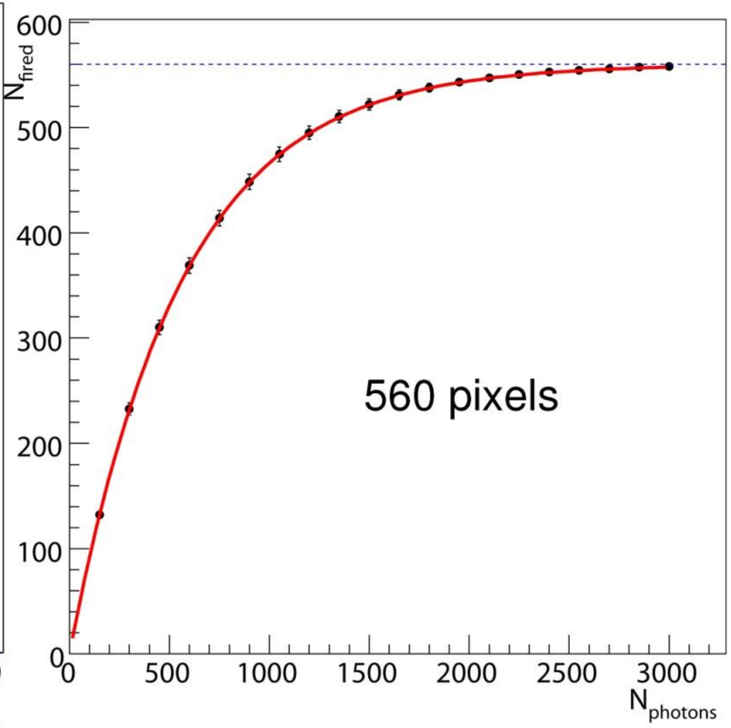


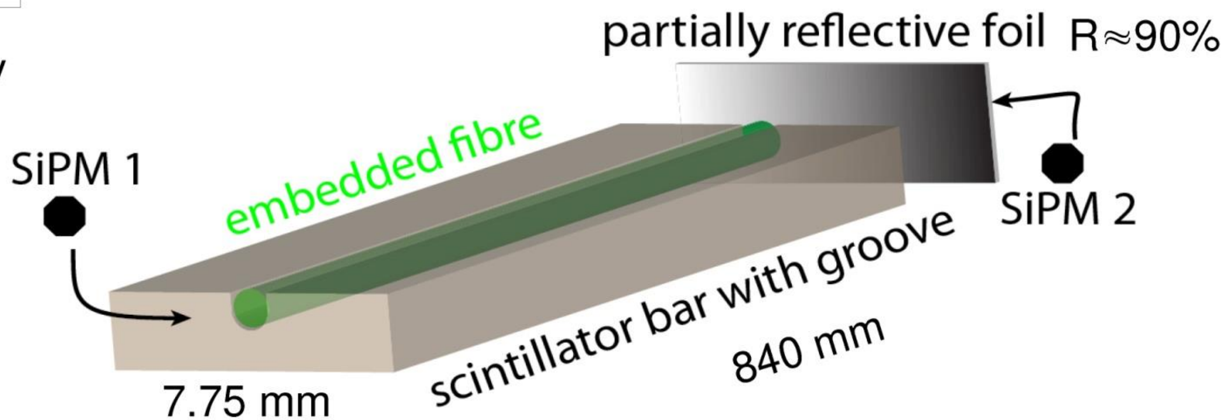
photons at fibre end



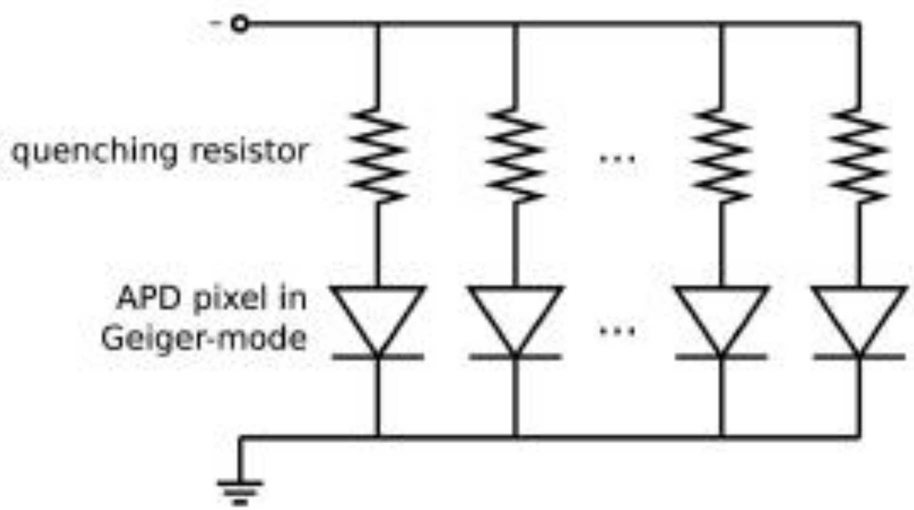
pixel array



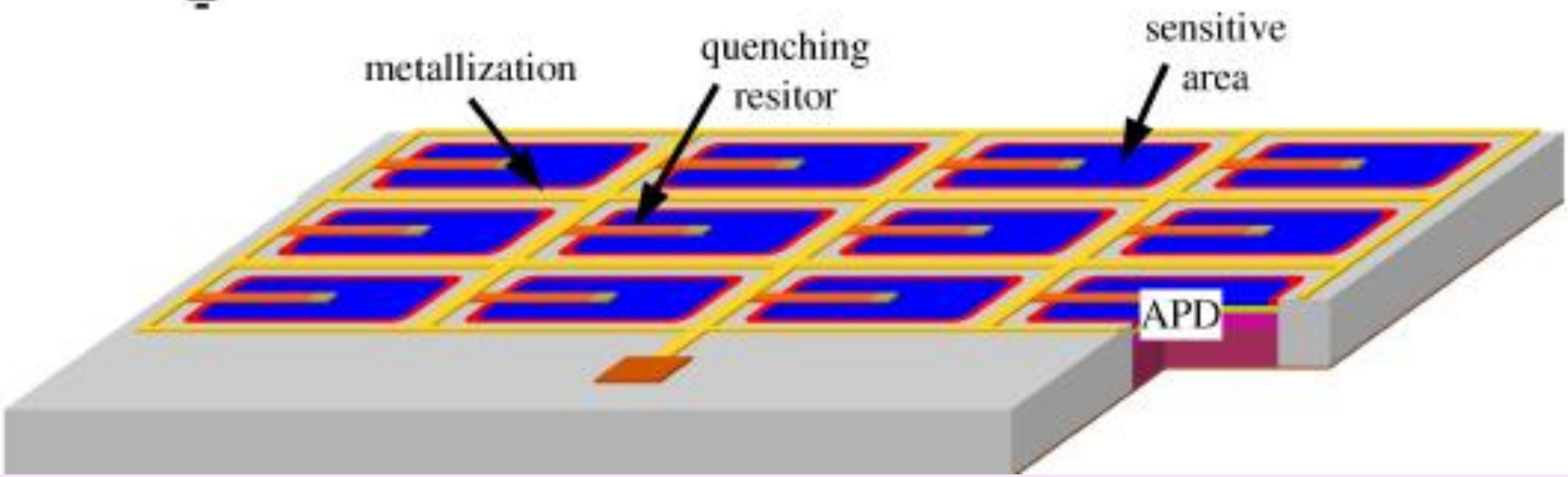




Silicon Photomultipliers (Geiger-mode APD)

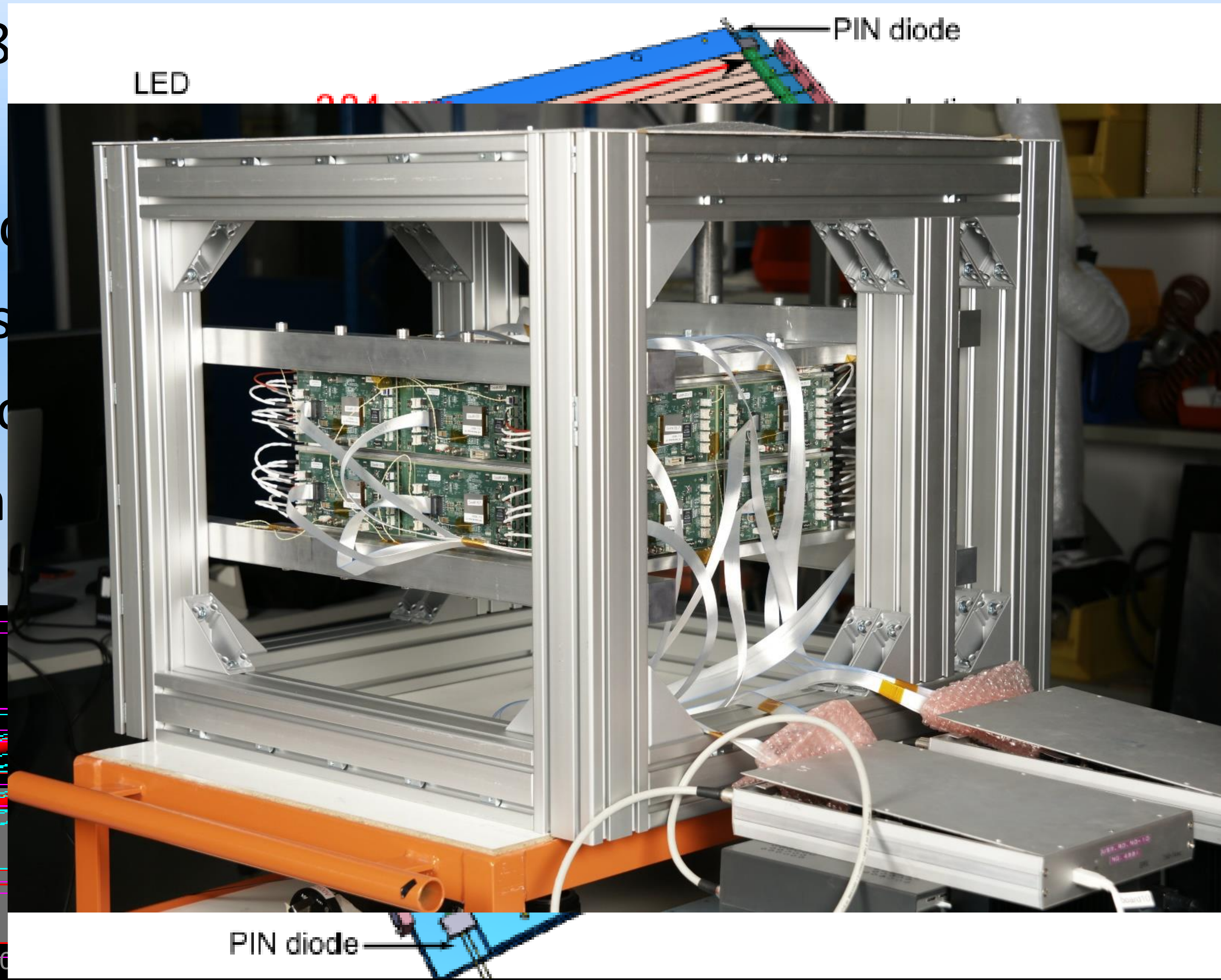


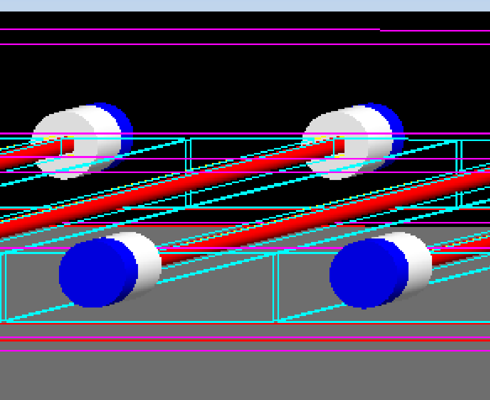
- avalanche photo diodes (APD) operated in Geiger mode
- internal gain ~10^6, compact in dimension, insensitive to magnetic fields, low bias voltage (<100 V)
- noise is an issue



ECAL Prototype Testbeam 2012

- New ECAL being constructed
  - Larger (38
  - 16 layers
  - Single elec
  - Two types
  - (Test of slo
  - 22 million



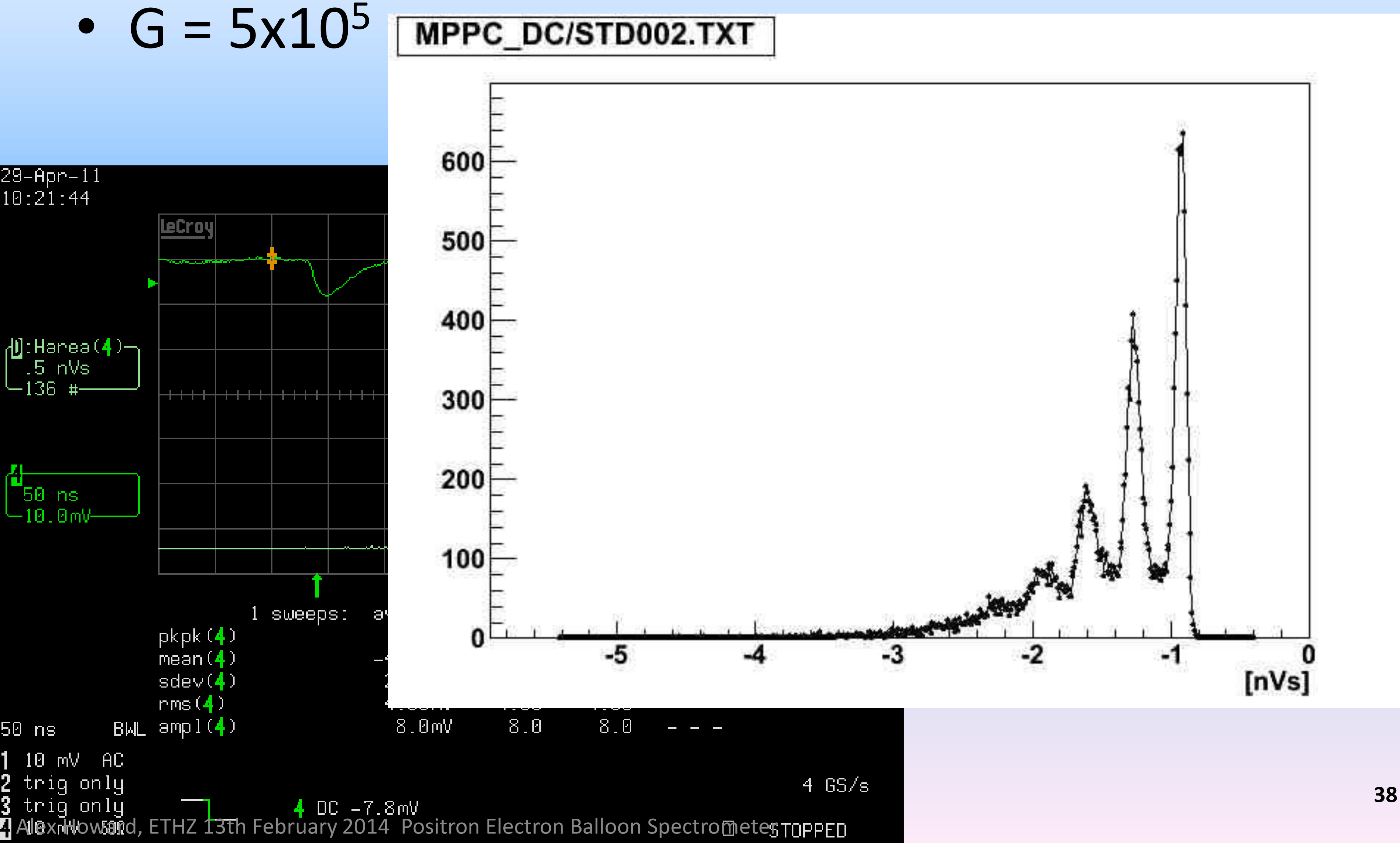


Two Type of SiPMs

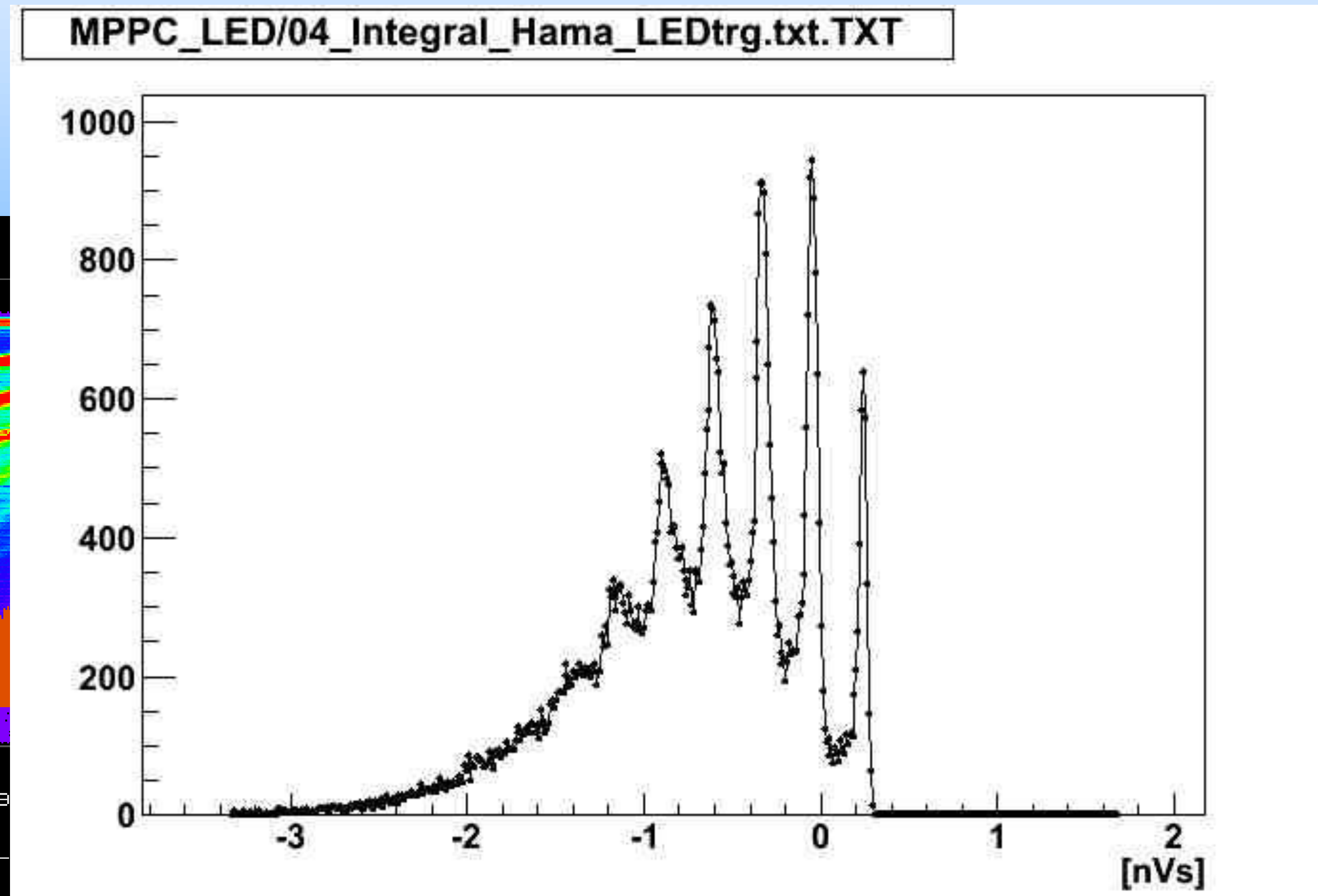
- Each end of the wavelength shifting fibre is read-out with different SiPMs
- One side is "standard" MPPC from Hamamatsu (1500 pixels/mm^2) - $G = 5x10^5$
- Second side is using Zecotek MAPDs - $G = 5x10^4$
  - New device
  - 15000 pixels/mm^2
  - Much higher saturation, lower gain
  - Unfortunately also higher noise

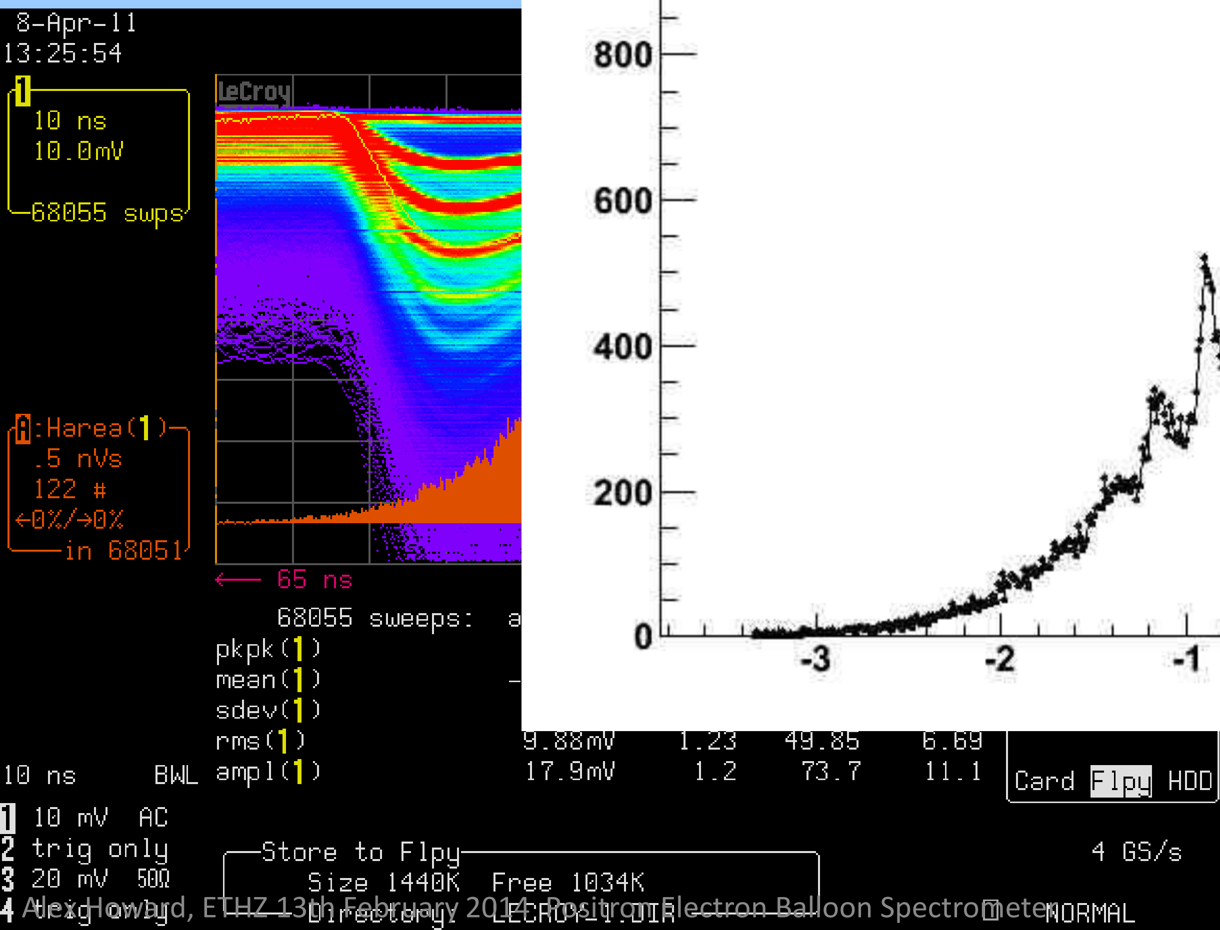
Hamamatsu MPPC

- Very clean signals
- G = $5x10^5$



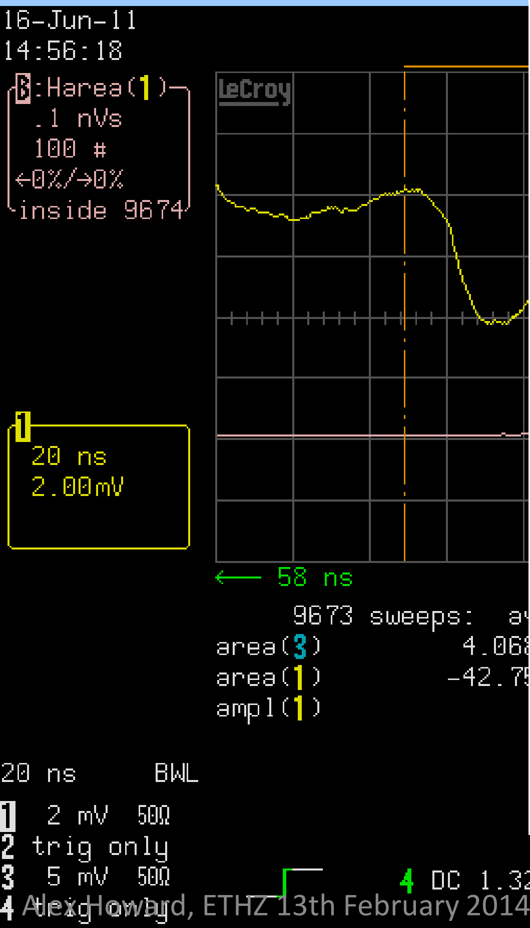
MPPC – LED pulsing

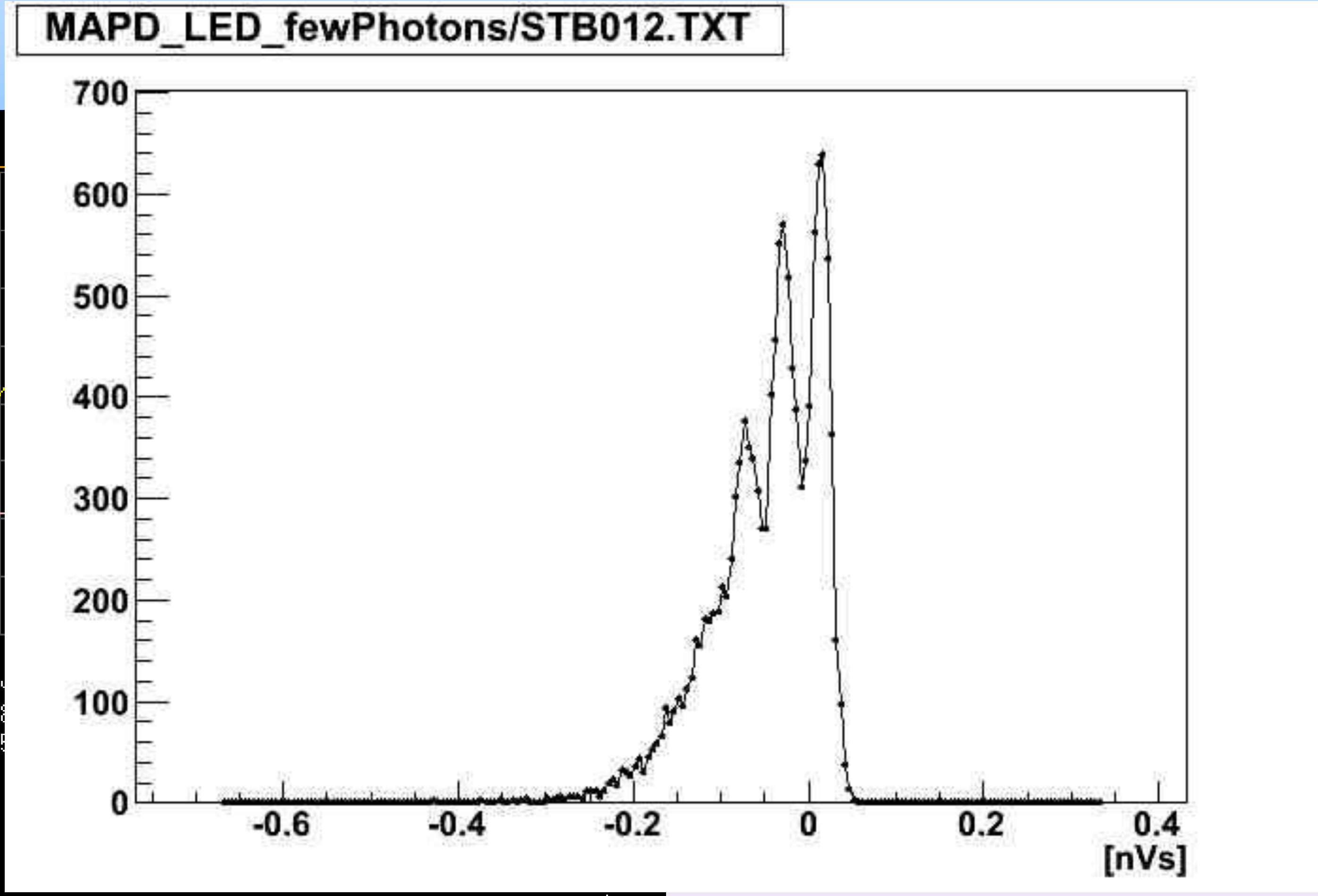




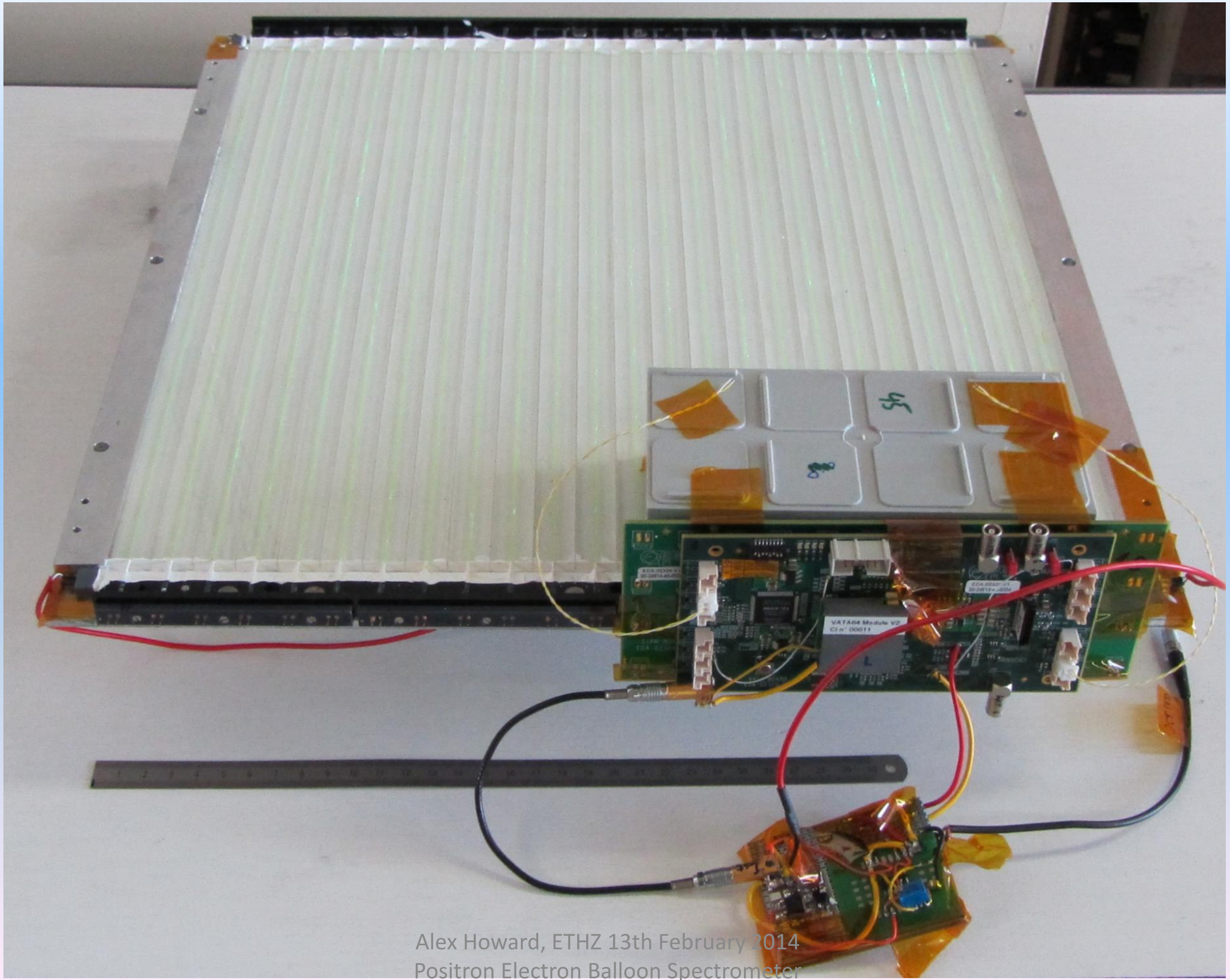
Zecotek MAPDs

- Noisier, Requires LED to see single photons
- G = $5x10^4$





Cosmic Muon Test

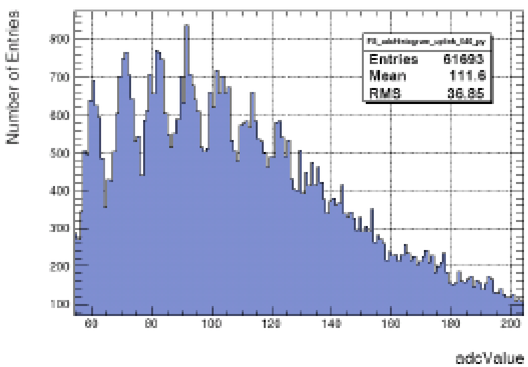


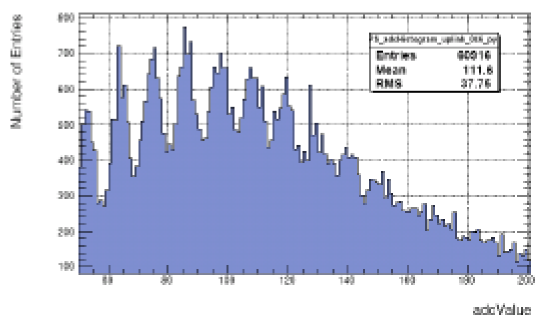
Muon (MIP) Response

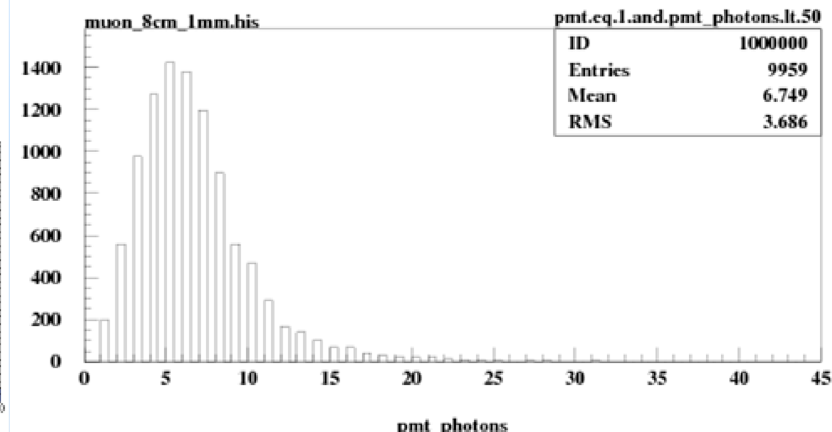
Run 23.12. 1M

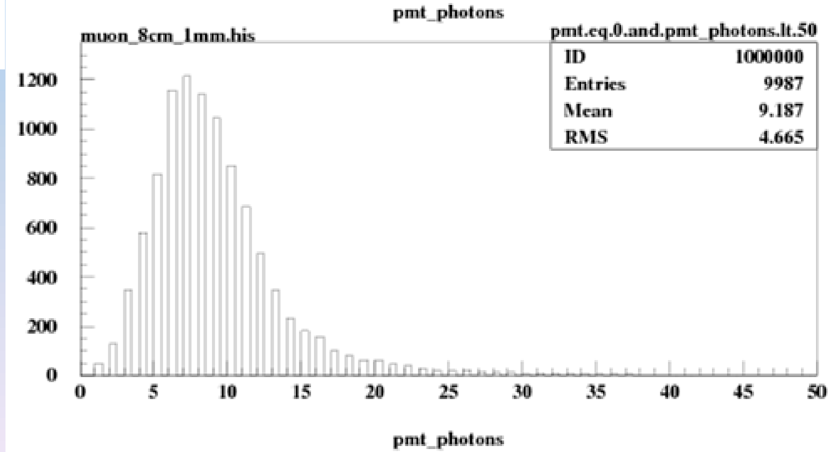
Ch13 is opposite Ch8, gain is

10ADC/PE, max @9PE



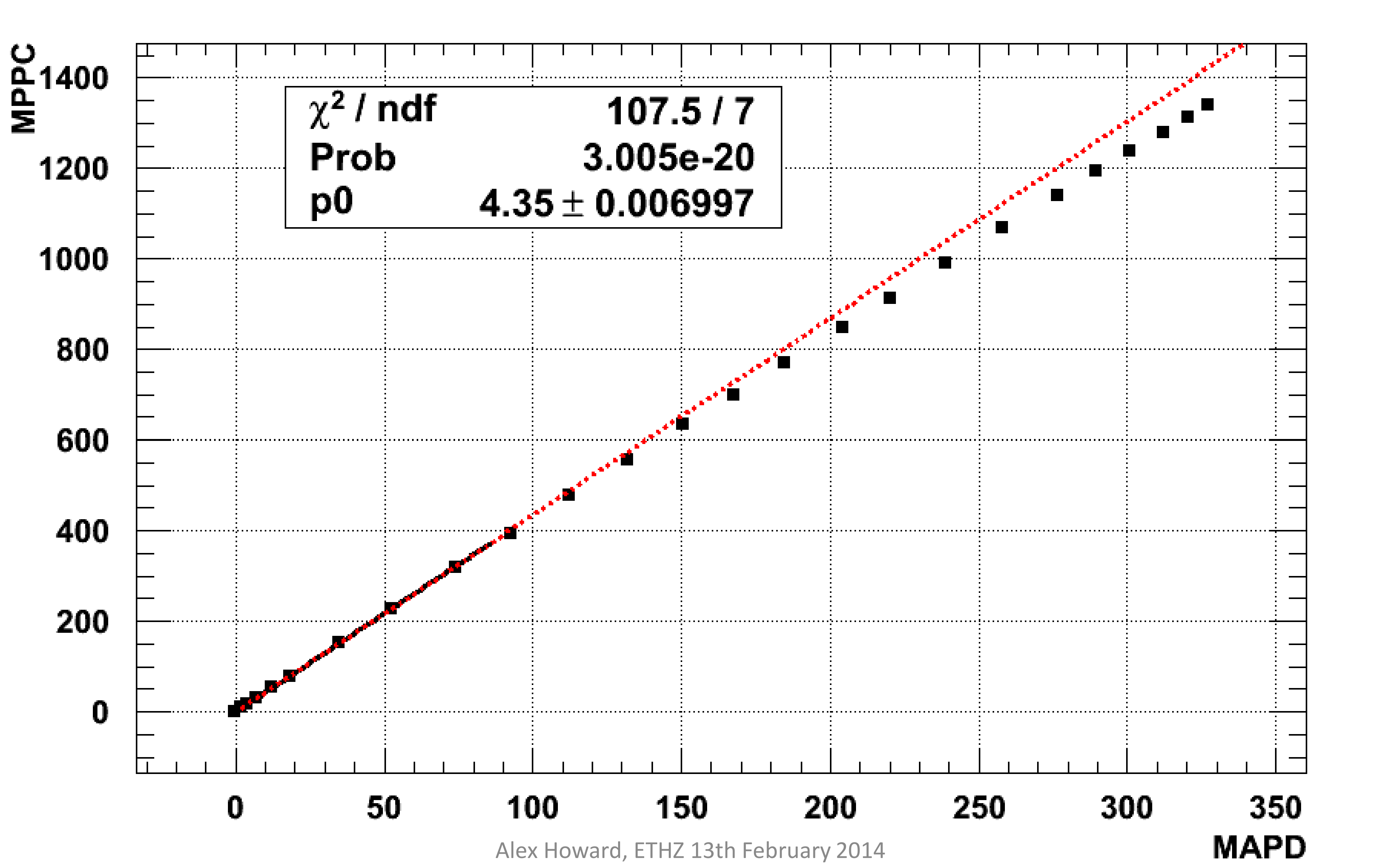






MPPC vs. MAPD

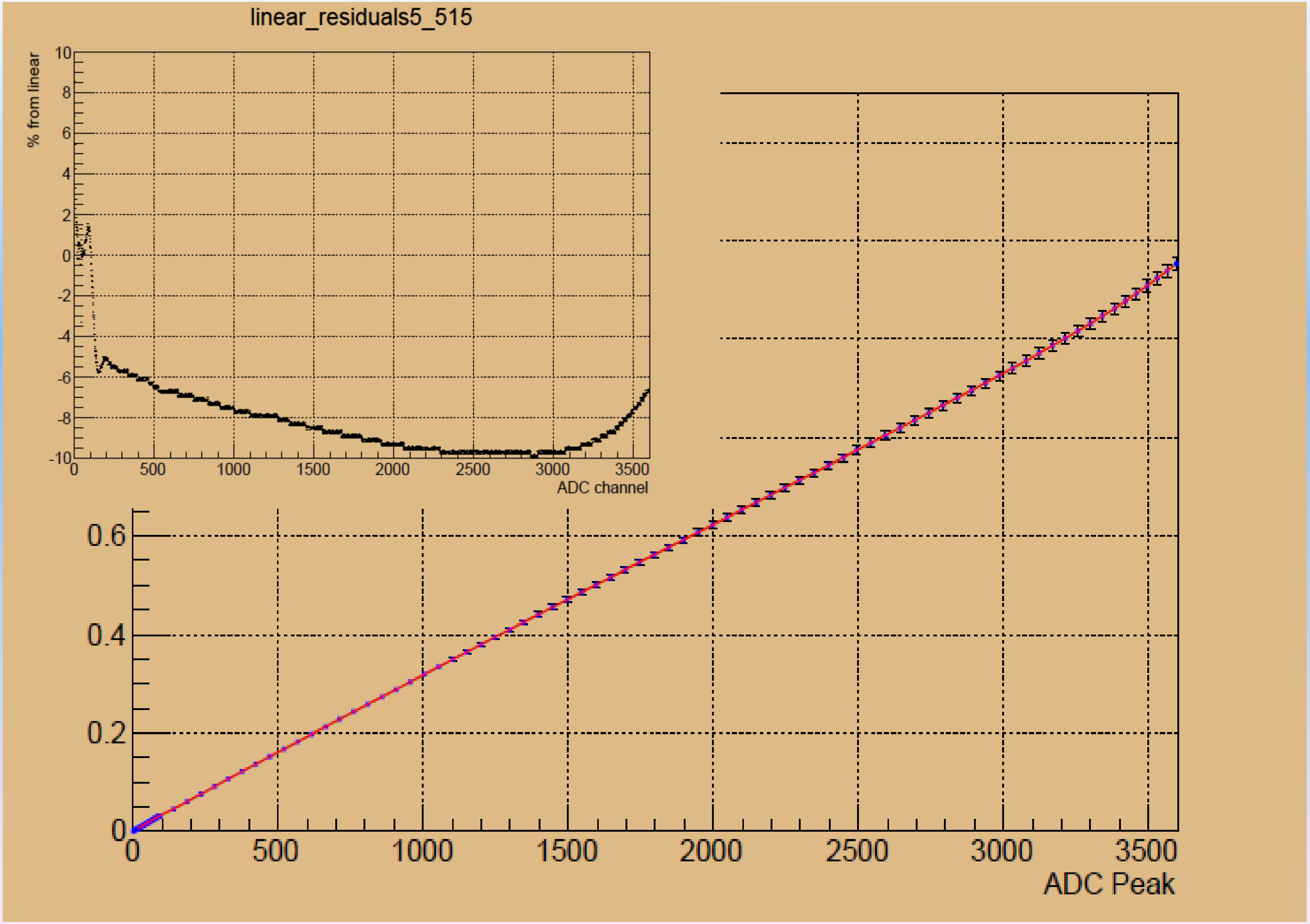
- MAPD does not saturate compared to MPPC



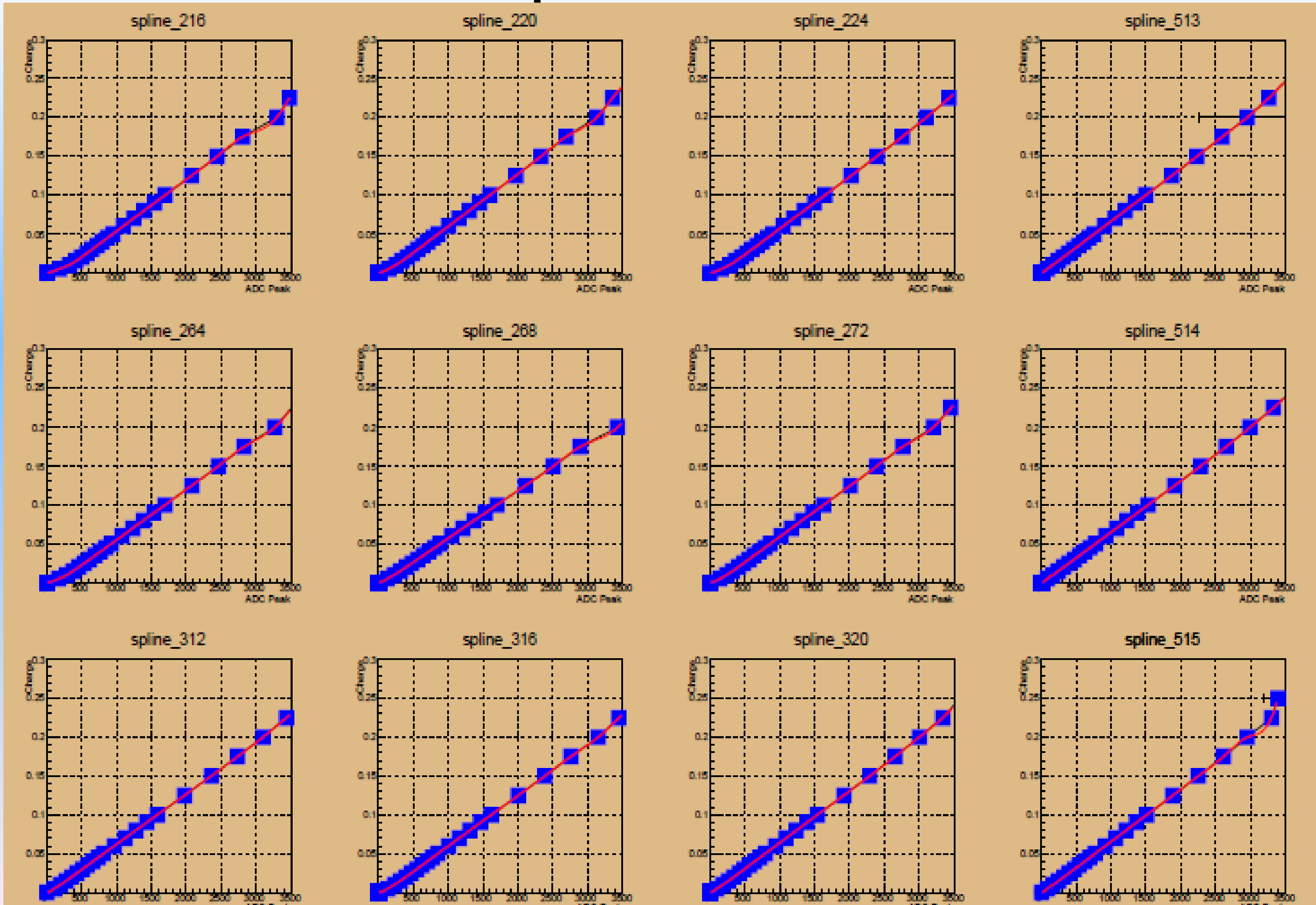
Amplifier non-linearity

- Unfortunately during the testbeam we found the amplifier had significant non-linearity
- Different slope at low amplitude and transition, with some channels chaotic
- Required precise charge injection and calibration across the full dynamic range
- Analysis ongoing, so only un-corrected data will be presented → worse energy resolution
- Shower shape, topology distorted
- Rejection factors need more work and M/C

Amplifier Calibration



Sample Channels



Testbeam Energy Measurement – MPPC and Low Energy (0.5 Gev, 2.5 GeV)

Use the longitudinal profile of EM-showers to be **robust to leakage**

Need Monte Carlo to use **last layer** => compensate for **no backscattering**

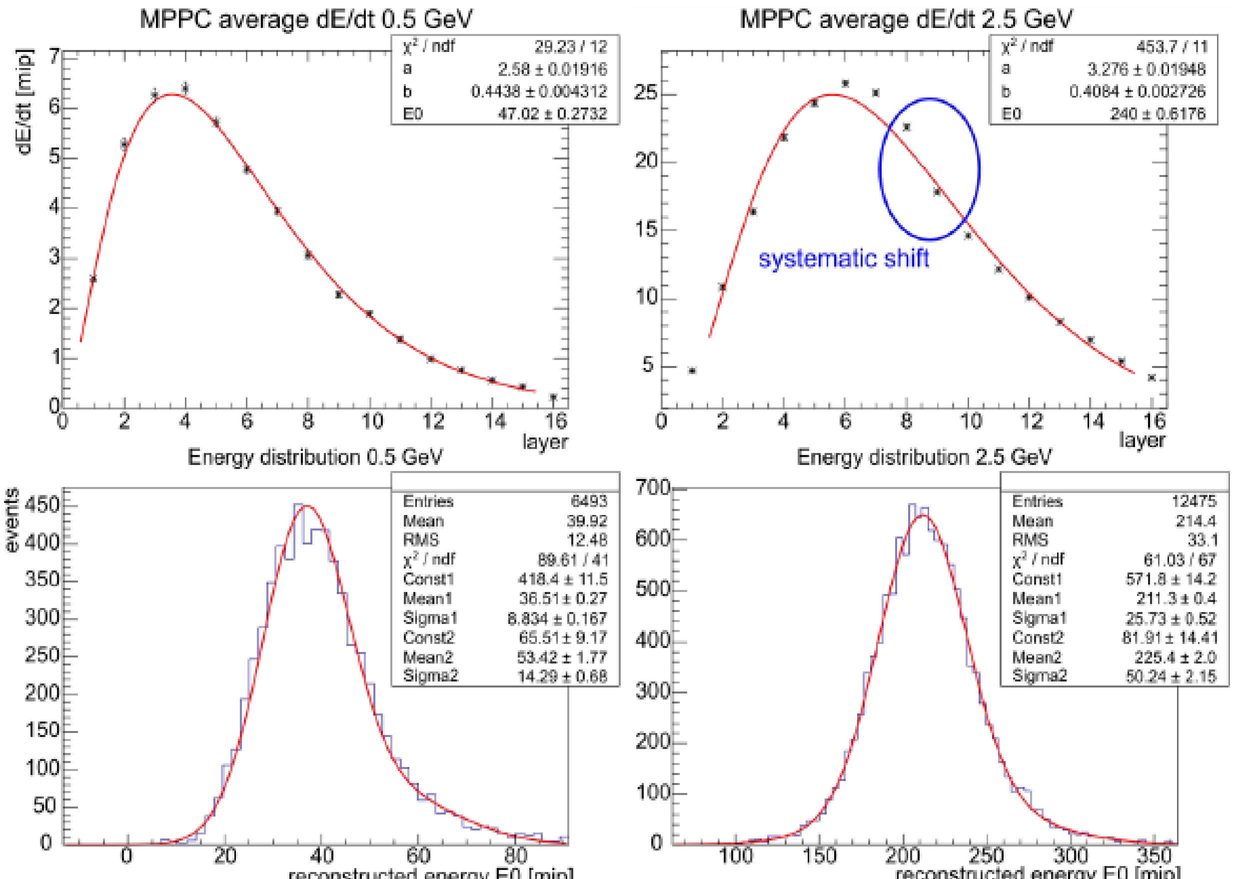
$$\frac{dE}{dt} = E_0 b \frac{(bt)^{a-1} e^{-bt}}{\Gamma(a)}$$

Systematic shift is a first sign of **amplifier non-linearity**

Double Gaussian energy distribution

Asymmetry at low energies due to **poor constraints** on E_0

=> must use 1^{st} layer



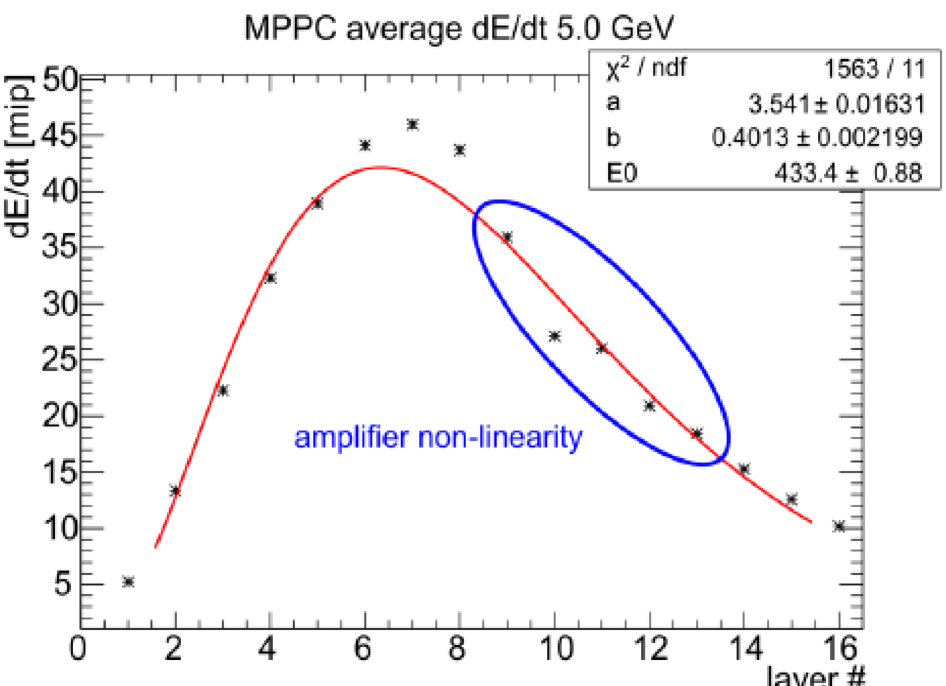
Victor Mikhalev

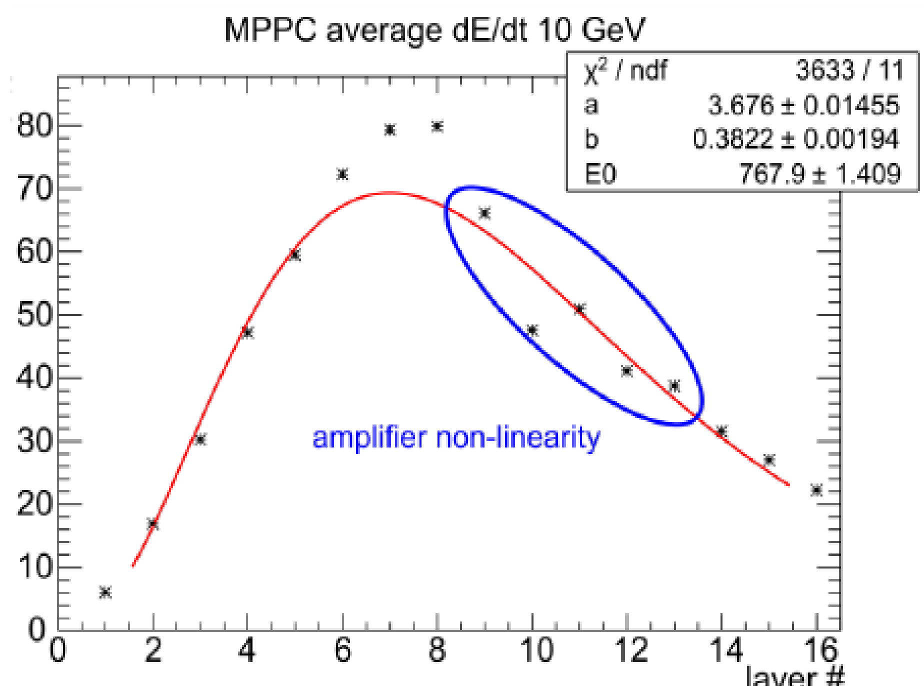
Amplifier Non-Linearity

Fluctuations are **not due to calibration** because it should produce a constant ratio

Layers 1-8 have a better performance

Previously known that non-linearity is **more severe for layers 9-16**





Victor Mikhalev

Energy Resolution

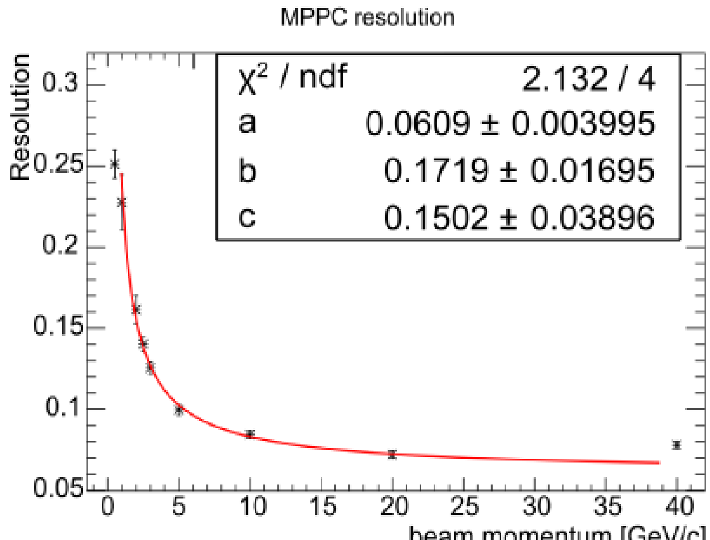
- 6% + 17%/√E (MPPC) and 6% + 20%/ √E (MAPD)

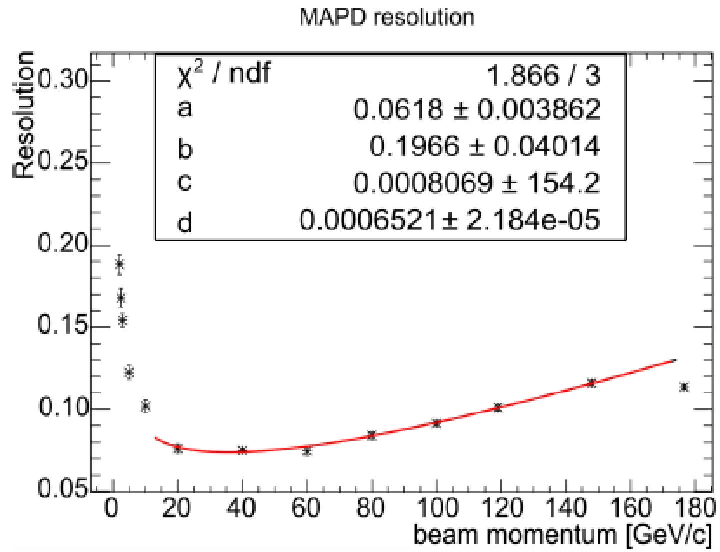
<u>Positive results:</u>

- Dual SiPM readout allows measurement of 0.5-180 GeV positrons => **<u>no saturation</u>**
- Use **MPPC** at low energies => **good resolution**
- Based on MPPC results the **calibration method works**
- At high energies measurements are typically limited by particle flux! => **large acceptance**

<u>Needs improvement:</u>

- Need **amplifier and temperature calibration** => improve resolution of both SiPMs
- **MAPDs** working at SPS but **broken** at PS may need a different calibration method
- WLS fiber has large variations in light capture efficiency => **revise gluing technique**





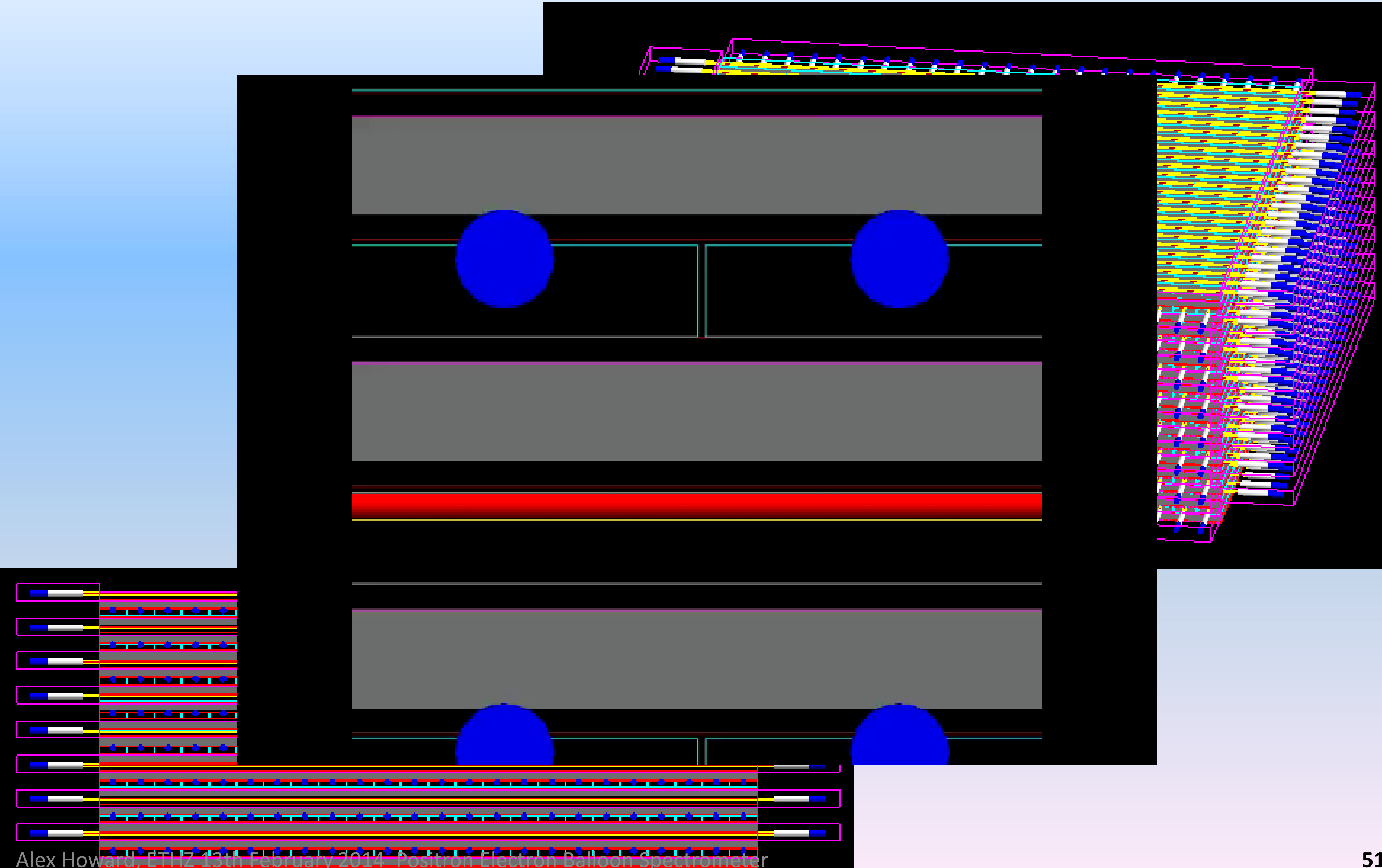
Proton Rejection Factors

- R-parameter:

  $\sum$ (bar_signal x layer)

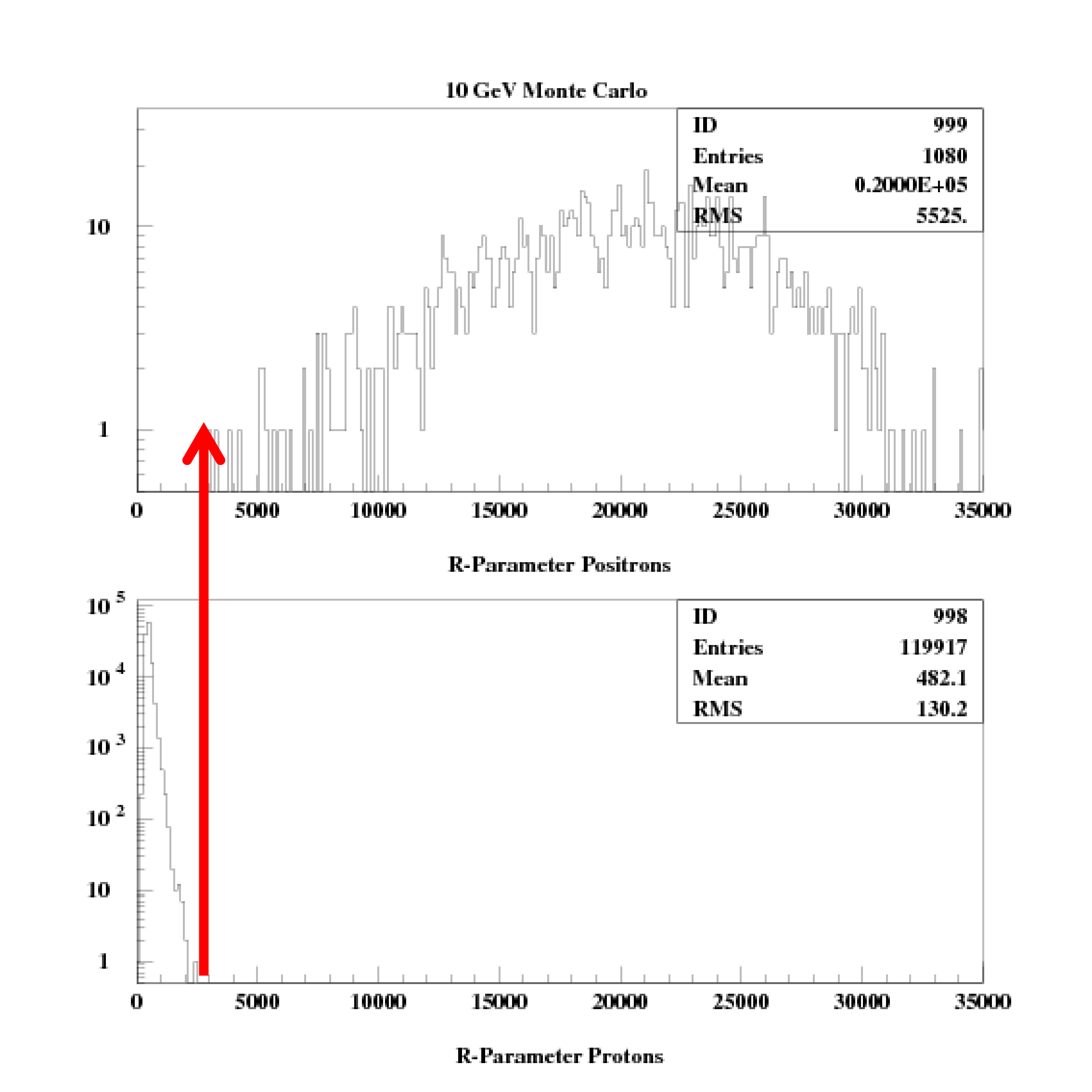
  within two Moliere radii and up to the shower maximum
- PAMELA used this approach
- AMS use a Boosted Decision Tree
- We have been exploring various techniques
  - Difficult to be transparent as any higher energy proton might generate a fake signal
  - Proton flux is up to a million times larger at high energy

Geant4 – Full ECAL Prototype



M/C Positrons vs. Protons

- Monte Carlo of test beam set-up
- 120000 protons do not give an electron-like signal
- @10 GeV
- Precise high energy studies compared to data ongoing



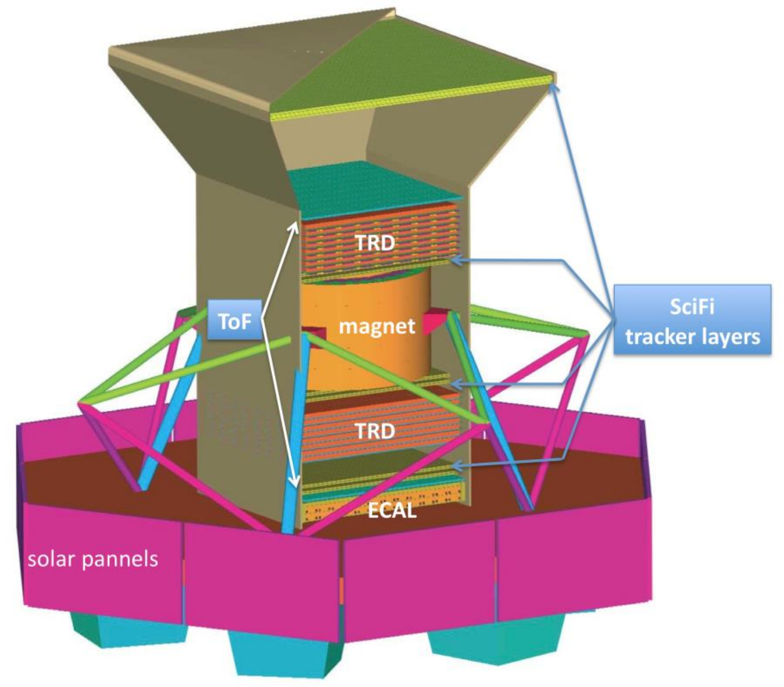
ECAL Status

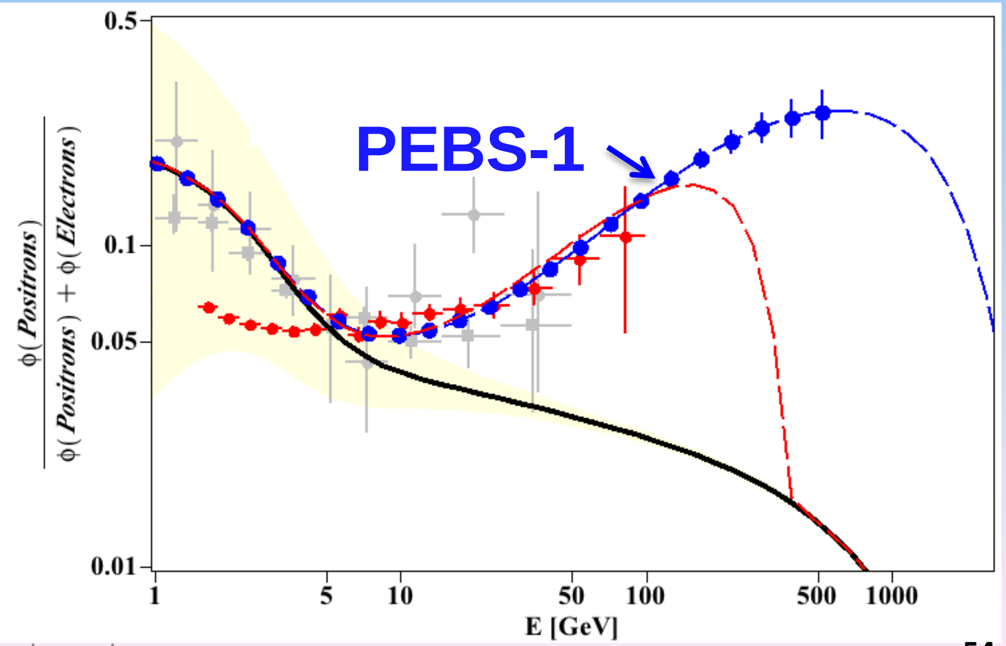
- Non-linearity of amplifier problematic, but now determined and correction implemented
- Proton rejection should exceed 10^3 (M/C)
- Energy resolution slightly below expectation:

  6% + 17%/√E (MPPC) and 6% + 20%/ √E (MAPD)
- Two SiPM read-out gives full dynamic range from MIPs up to several thousand without evidence of saturation!
- Would be a viable ECAL for a small scale PEBS
- Analysis still ongoing

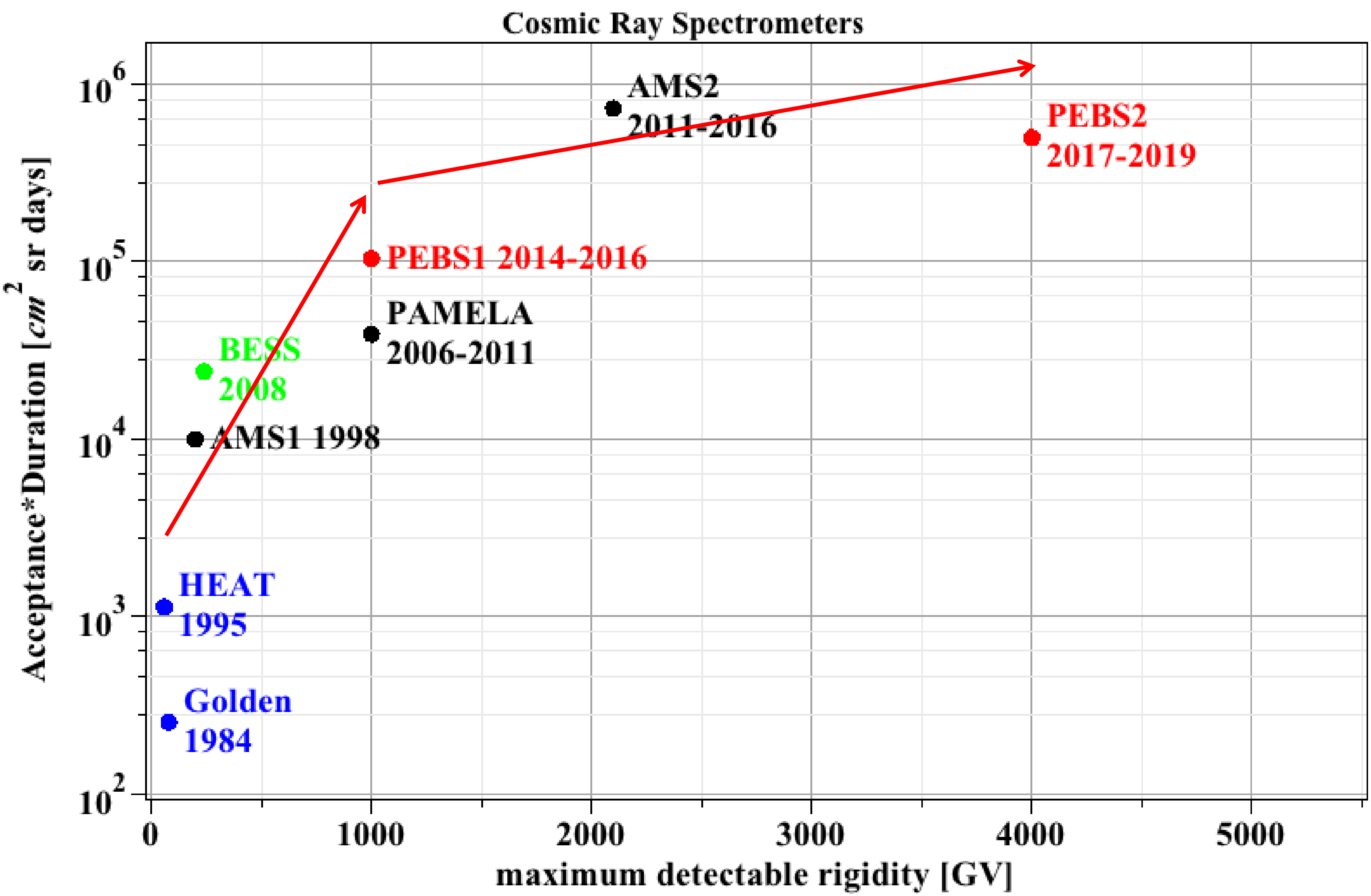
PEBS Summary

- A dedicated balloon experiment could provide a competitive measurement of the cosmic ray electron & positron flux.
- The spectrometer is based on a scintillating fiber tracker with SiPM readout and a permanent magnet.
- The proton rejection of ~10^6 can be achieved by a combination of ToF, TRD, ECAL and Tracker.
- Key parameters:
  Acceptance: ~1200 cm^2 sr
  Weight: ~2000 kg
  Power: ~900 Watt
- R&D Phase:
  ongoing – testbeam successful…
- Construction Phase:
  Detector components exist
- First PEBS Flight: 201?





Bigger and Better?



Physics Prospective

- PEBS **scalable design** allows a further increase in the geometric acceptance
- Able to use **superconducting** magnet
- Very high saturation threshold enables measurement of **TeV scale energies**
- Need a **long duration balloon flight**
- Balloon flight is complementary with AMS02 => **different area of the sky**

- May distinguish between pulsar and Dark Matter models!

Pulsar

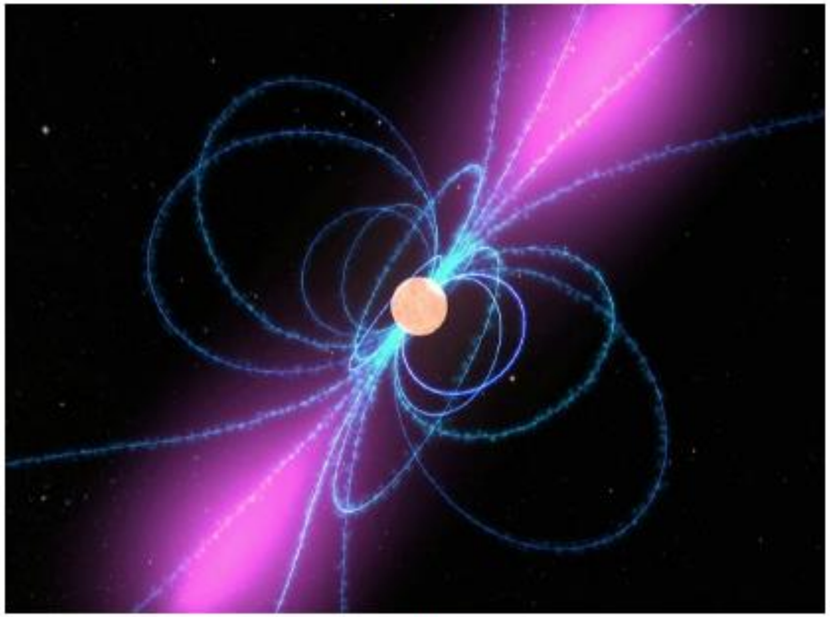


Image courtesy: artist's impression, NASA

Dark Matter

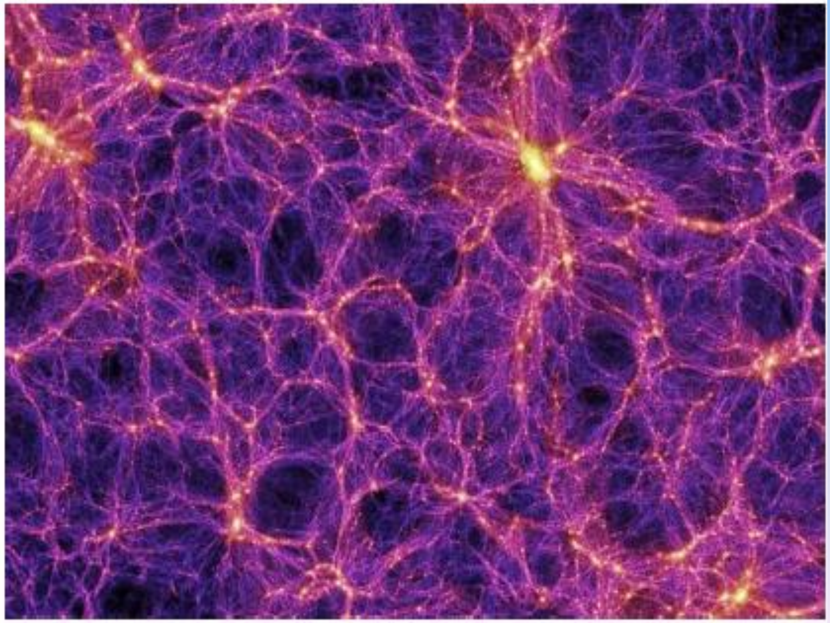


Image courtesy: Volker Springel Millennium simulation

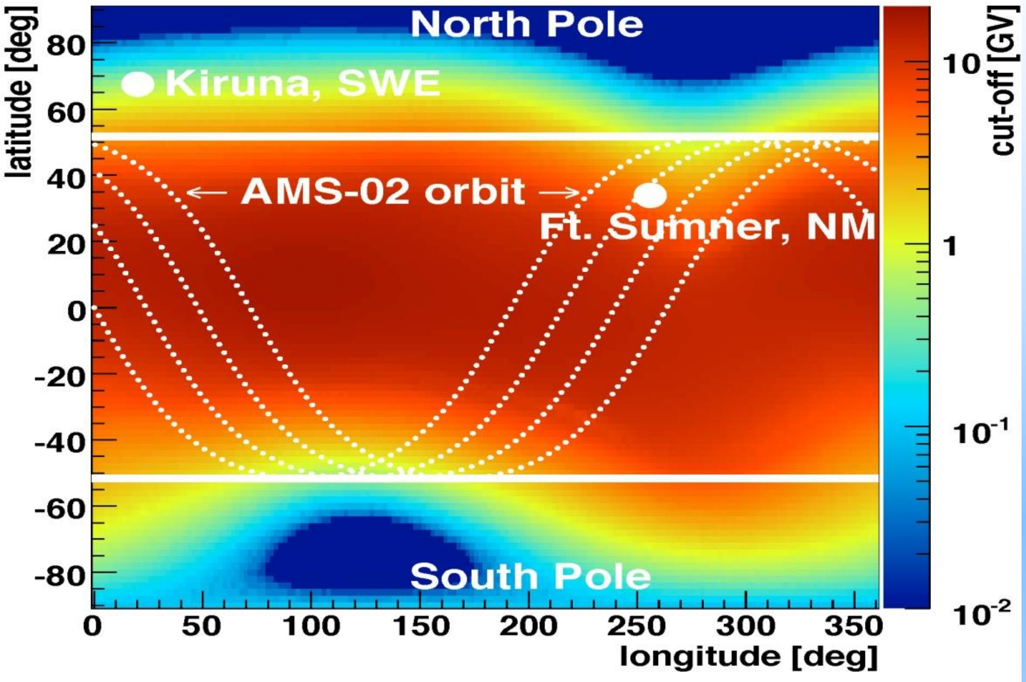
Conclusions

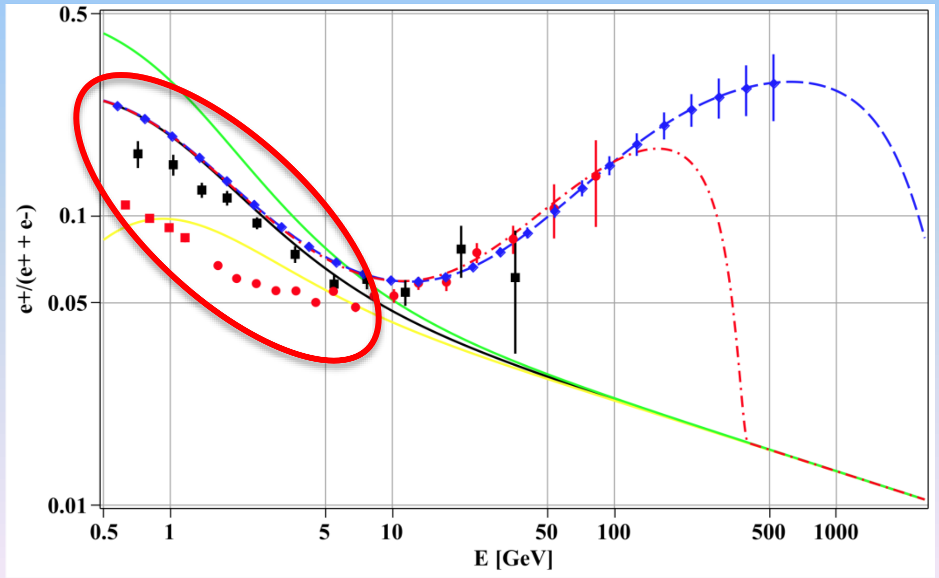
- PAMELA first measured a discrepancy in the positron fraction at high energy
- FERMI-LAT confirmed, AMS recently extended spectrum
- Dark Matter annihilation could be one explanation
- Balloon borne spectrometers offer a very good way to extend the measured spectrum up to the TeV scale
- A novel ECAL has been developed using two types of SiPMs
  - $6\% + 17\%/\sqrt{E}$ (MPPC) and $6\% + 20\%/\sqrt{E}$ (MAPD)
- Could be an exciting time for balloon measurements…

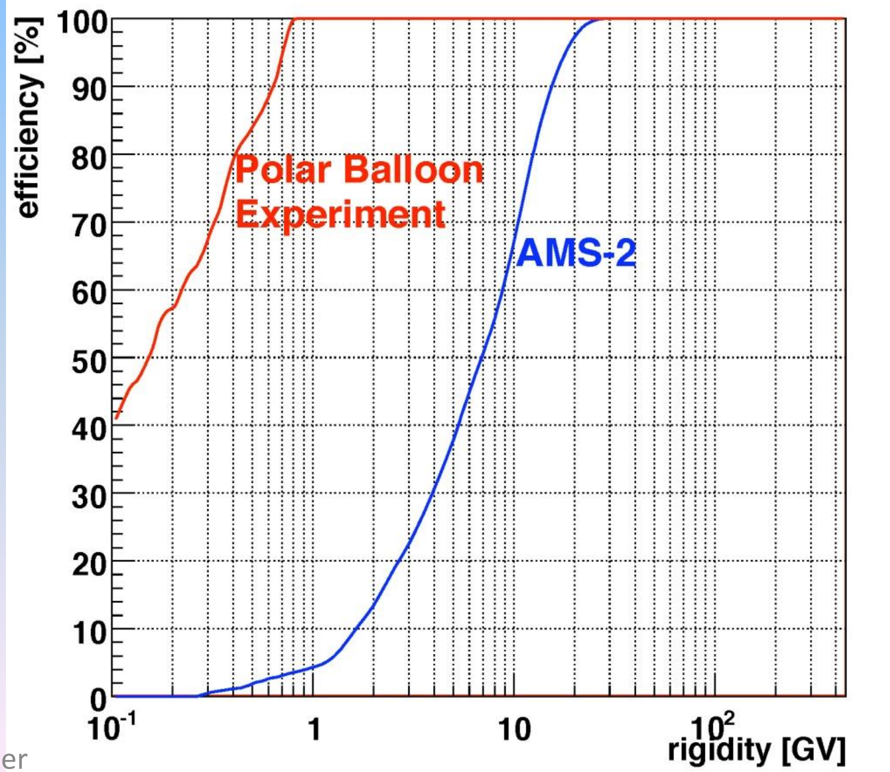
Thank you for your attention!

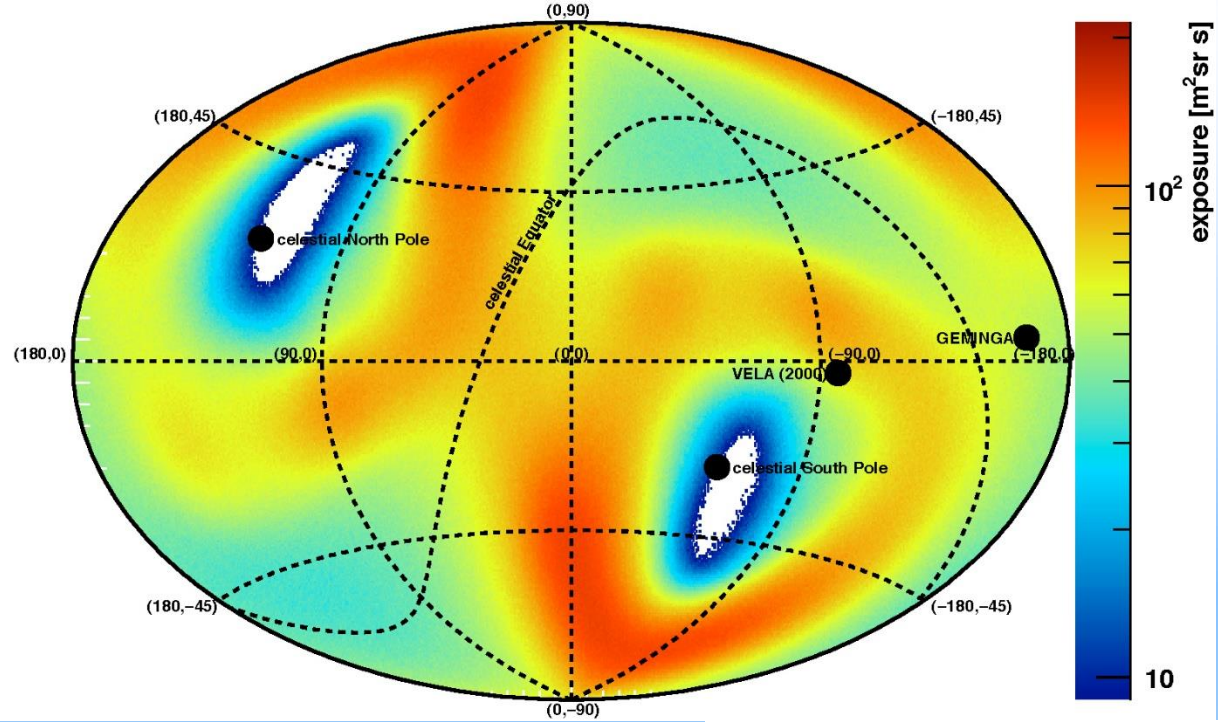
Back Up Slides

Geomagnetic-Cutof



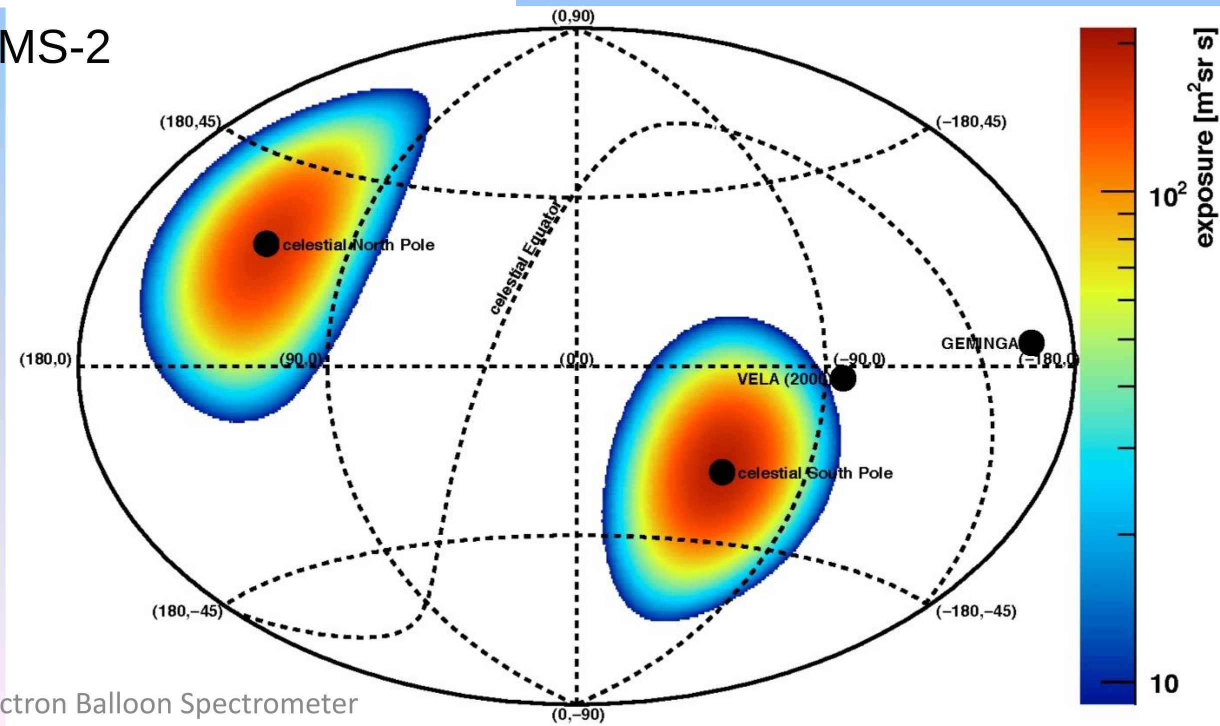






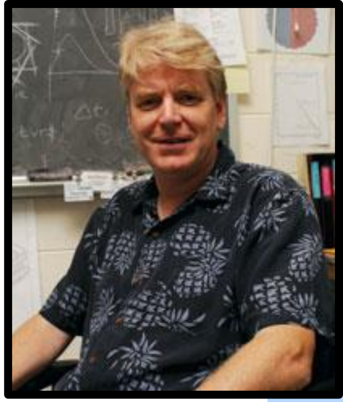
Skycoverage of PEBS

Skycoverage of AMS-2



(NNH09ZDA001N)
ASTROPHYSICS RESEARCH AND ANALYSIS PROGRAM
(APRA-2009)
PANEL EVALUATION

Proposal No.: 09-APRA09-0085
PI/Institution: Swordy, Simon P / University of Chicago
Proposal Title: The Positron Electron Balloon Spectrometer (PEBS)



Overall Summary of Evaluation:
This research is important in the search for indirect dark matter annihilation signals and evidence of nearby cosmic-ray sources, and in constraining propagation models in the 1 to 500 GeV energy range.
The proposed investigation has the potential to resolve a number of questions that have been raised by recently reported anomalies (relative to standard cosmic ray models) in the all-electron spectrum and the positron fraction at high energies. Only with a concerted experimental effort on the scale of that proposed can one expect to definitively answer the question of whether these anomalies are due to systematic errors in what are clearly very difficult measurements, or whether they represent the signature of new, important physical phenomena.
This state of the art instrument will cover a wide energy range, and it would have the needed proton rejection for making background-free observations of electron and positron spectra in a very important energy range. The AMS-2 experiment, scheduled for launch to the Space Station in early 2011, will also address these objectives with a comparable complement of sensors. **The collecting power of AMS-2 will be smaller, but it will have a substantially longer exposure, and it will not be subject to backgrounds from secondary particles produced in the atmosphere. Consistent results from these two experiments could conclusively settle the present questions about the positron and electron spectra below 1 TeV.**

<u>OVERALL ADJECTIVAL RATING</u>: Excellent

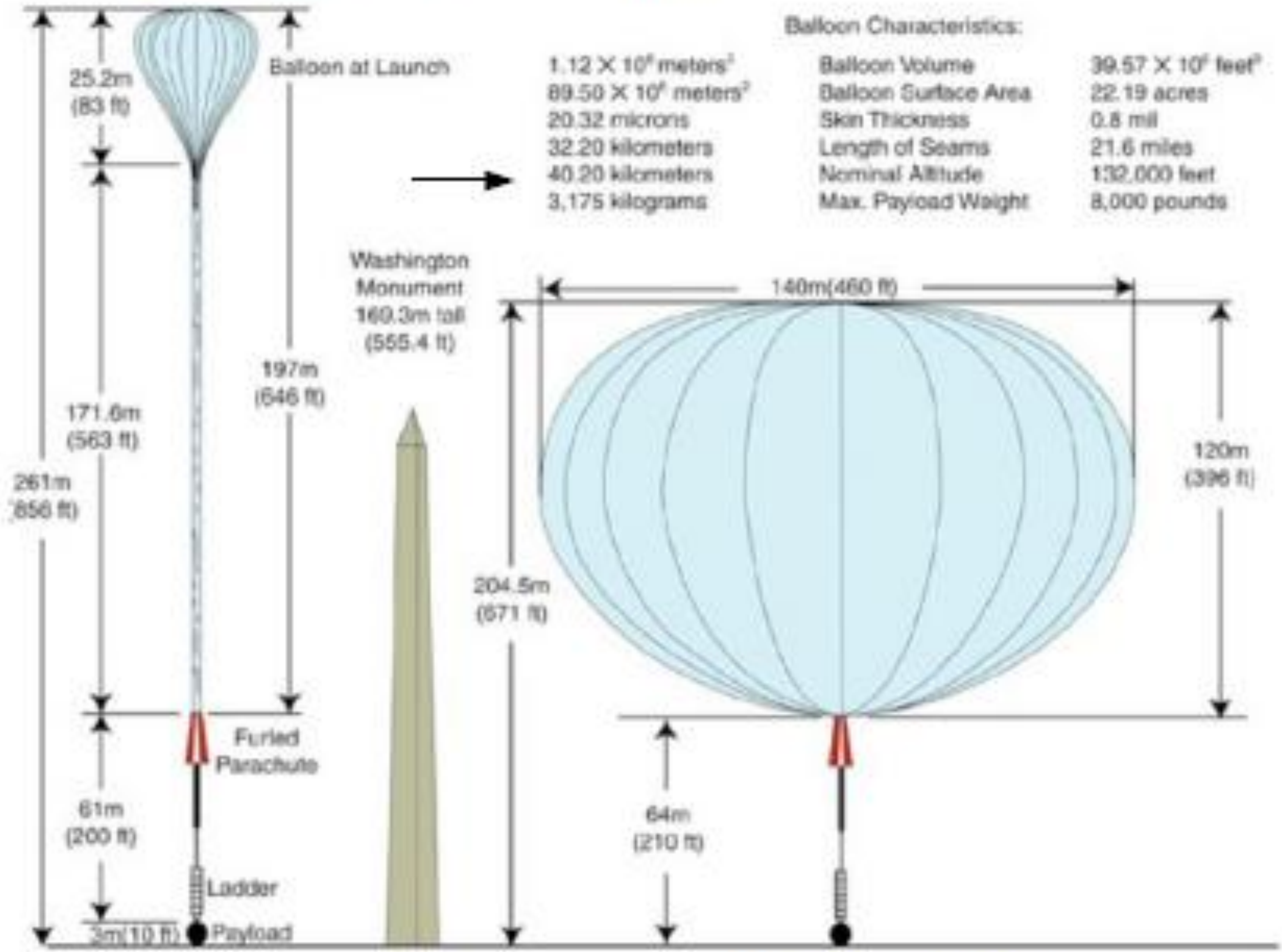
Large Size, Short Duration

Cosmic Ray Experiments

	Acceptance [cm2 sr]	Duration [days]	Electron Identification
PAMELA	20	1000	Spectrometer + ECAL
AMS-2:	850	1000	Spectrometer + ECAL + TRD
PEBS-1	1000	10	Spectrometer + ECAL + TRD
ATIC-2:	1500	20	ECAL
PEBS-2	3000	40	Spectrometer + ECAL + TRD
PEBS-1	7500	10	ECAL + TRD
FERMI	25000	2000	ECAL

25/01/10 5353

PEBS: Balloon-borne experiment



Weight ~2000 kg

AMS BDT Rejection Analysis